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

Critical Design Review

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Customer: Dr. Xu Wang, Dr. Zoltan Sternovsky
Advisor: Dr. Torin Clark

Project Purpose and Objectives

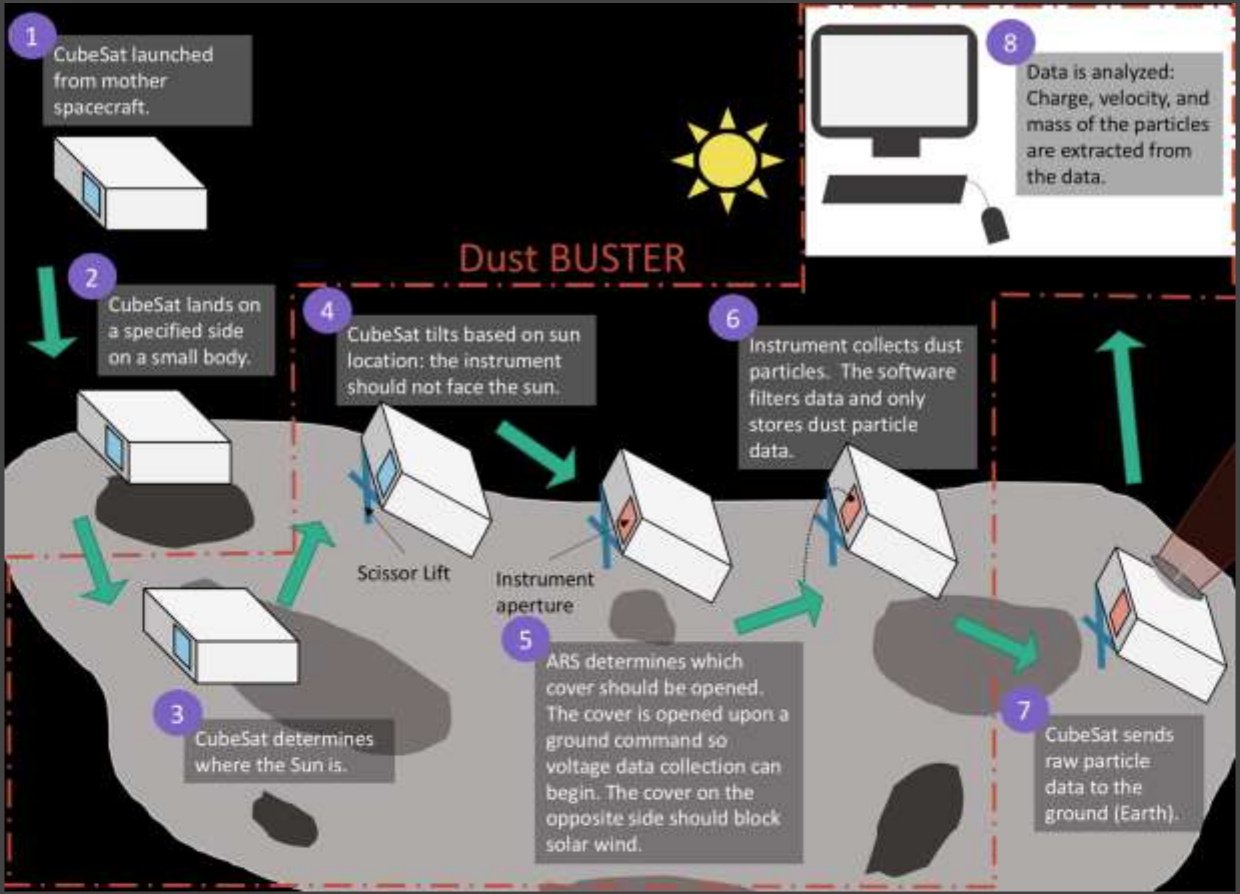
Project Motivation

- 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

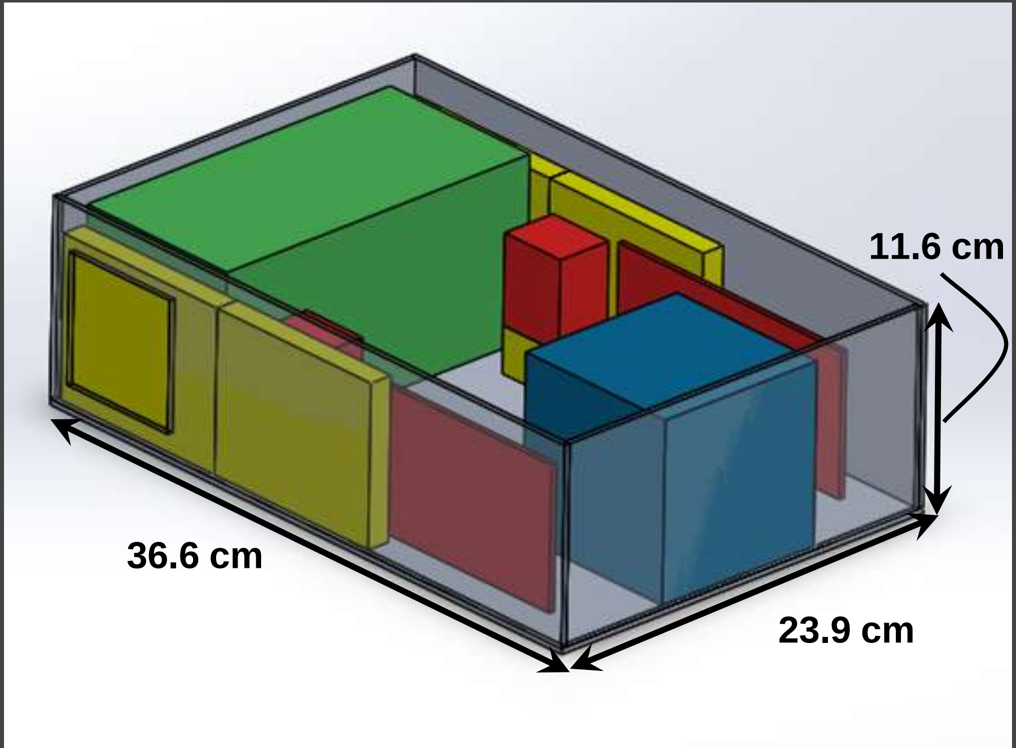


Functional Requirements

FR 1	The CubeSat model shall contain the Autonomous Repositioning System (ARS) and 2U instrument within 6U volume and mass limits.
FR 2	The instrument shall detect dust particles that enter the instrument.
FR 3	The Autonomous Repositioning System (ARS) mechanisms shall open the instrument door that is pointing away from the sun.
FR 4	The Autonomous Repositioning System (ARS) mechanisms shall tilt the instrument boresight up to a maximum of 45° off the surface.
FR 5	The electronics subsystem shall collect signals and issue commands to and from the instrument and Autonomous Repositioning Systems (ARS).
FR 6	The software shall be capable of data processing, detecting dust events, and running Autonomous Repositioning System (ARS) algorithms.

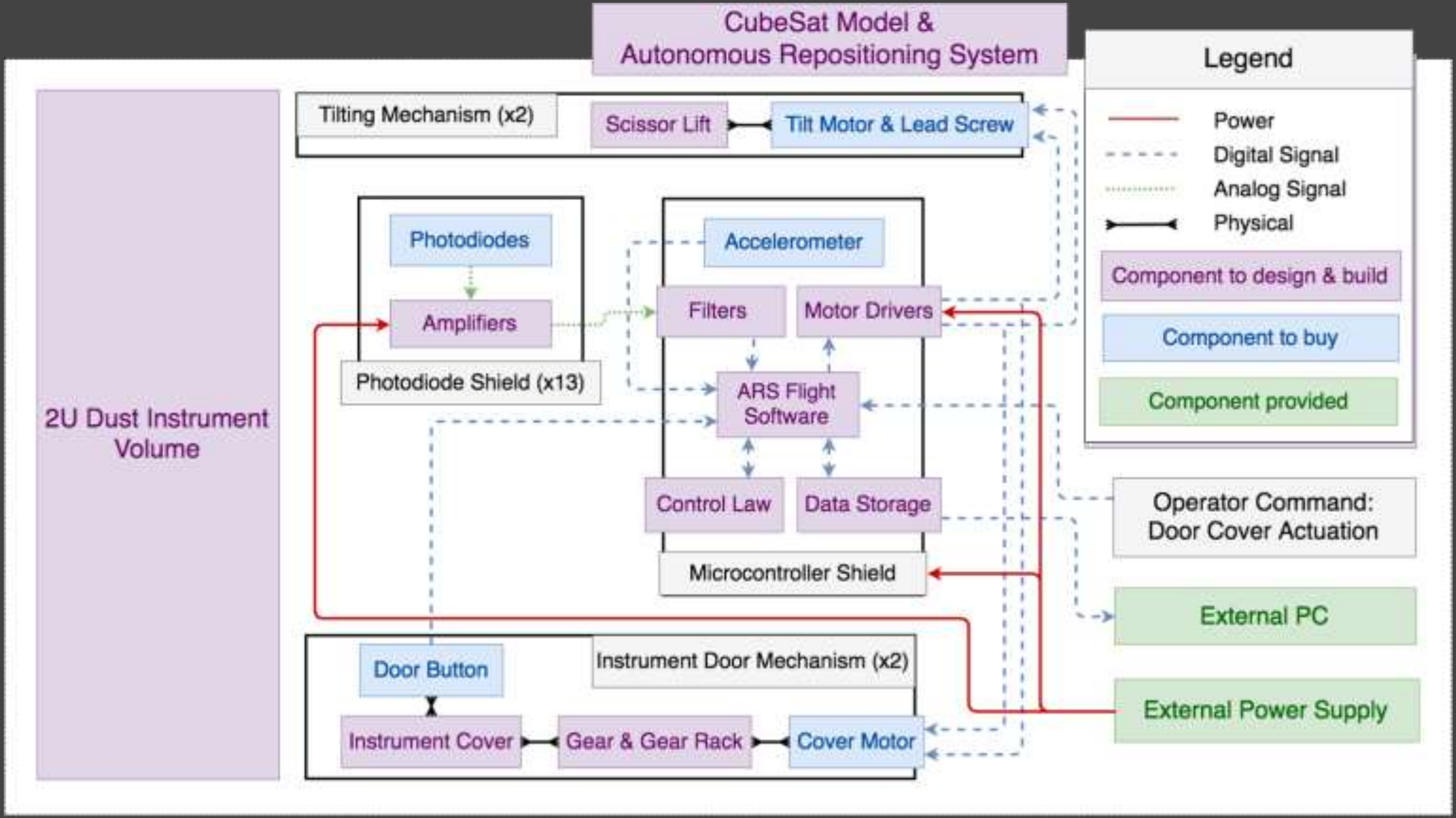
Design Solution

Project Purpose | Design Solution | Design Requirements | Project Risks | Verification and Validation | Project Planning



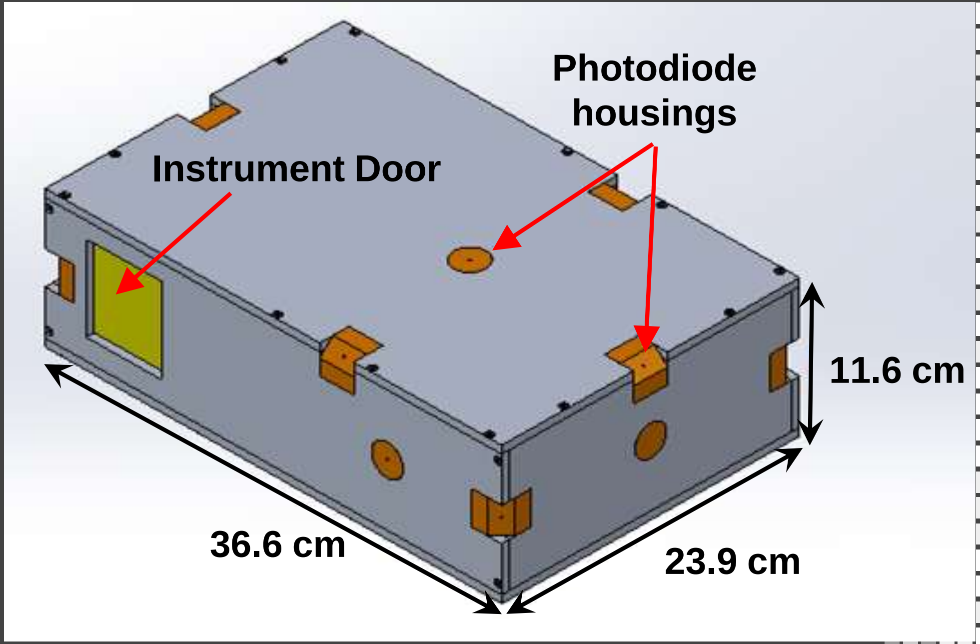
System	Color
Dust Instrument	
Door Mechanism	
Scissor Lift Mechanism	
Avionics (Out of Scope)	

Autonomous Repositioning System FBD



CubeSat Model

- **Purpose**
  - Structurally house all project subsystems
- **Design**
  - 6061 aluminum box bolted together
  - Subsystems bolted to the interior
- **Current Specs**
  - Dimensions: 36.6 x 23.9 x 11.6 cm
  - Mass: 10.20 kg total out of 12 kg requirement



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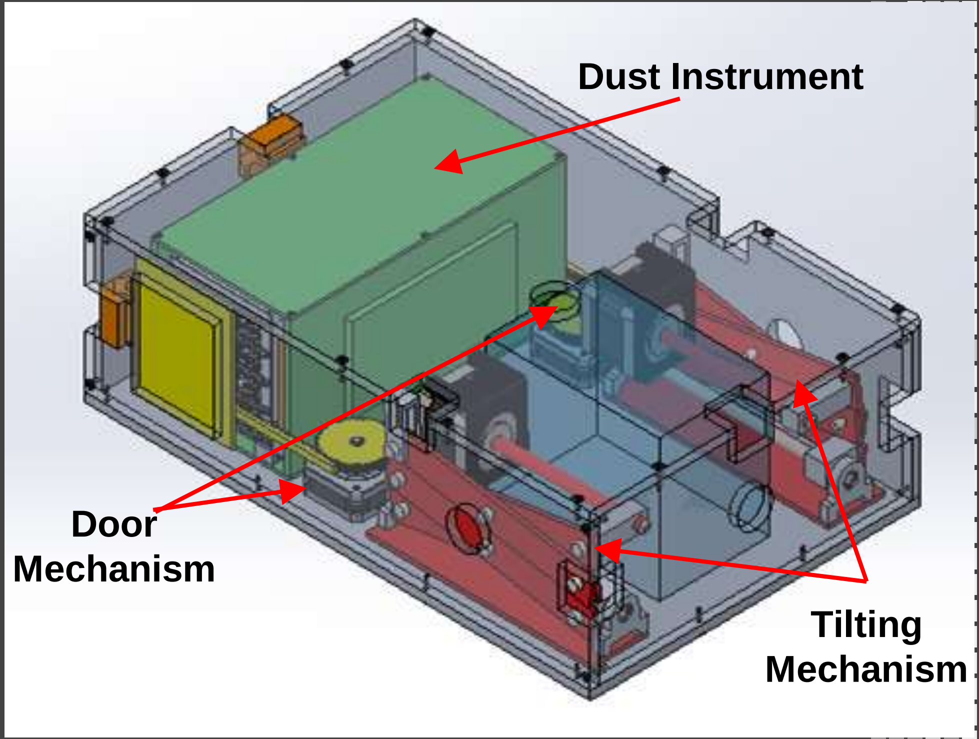
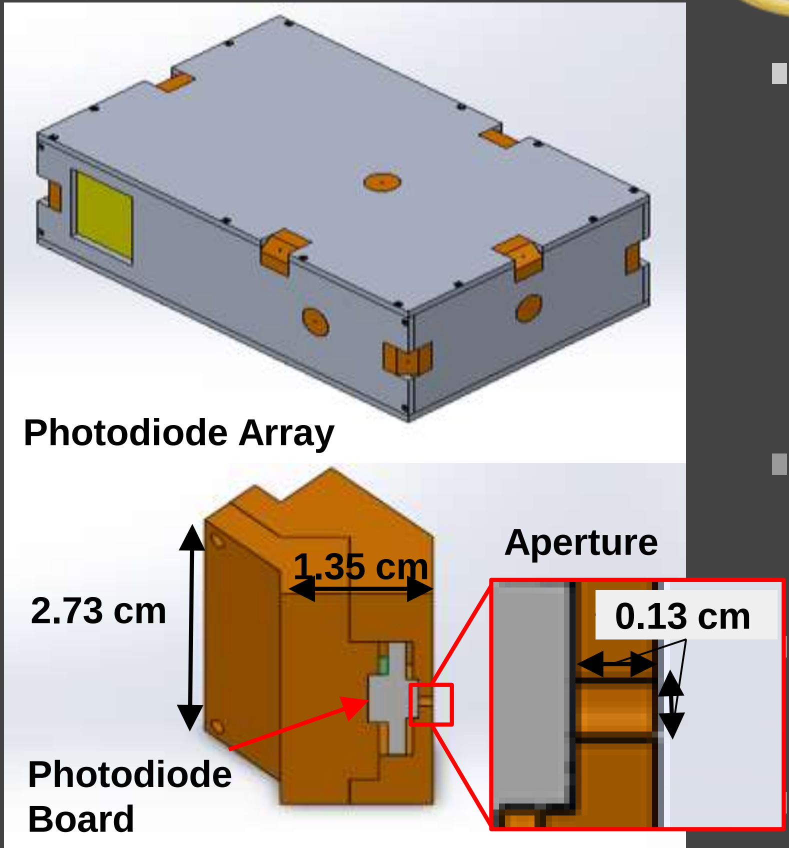


ARS Sensors and Software

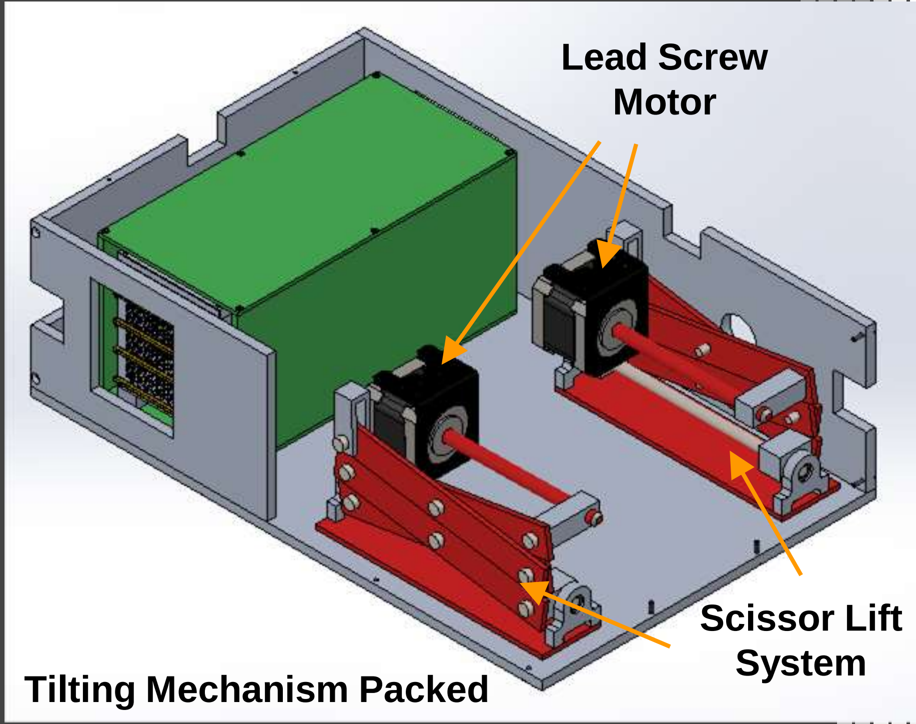
- **Purpose**
  - Determine sun vector
  - Determine tilt angle
- **Design**
  - Photodiodes with housings
  - Accelerometer
  - Software finds sun vector, implements controls
- **Current Specs**
  - 13 photodiodes
  - Accelerometer mounted on microcontroller shield



Photodiode Structure X-section

Tilting Mechanism

- **Purpose**
  - Achieve up to 45 degree tilt
- **Design**
  - Stepper motor with lead screw
  - Aluminum scissor lift
- **Current Specs**
  - Mass: 0.6195 kg per side
  - Motor torque: 0.26 Nm



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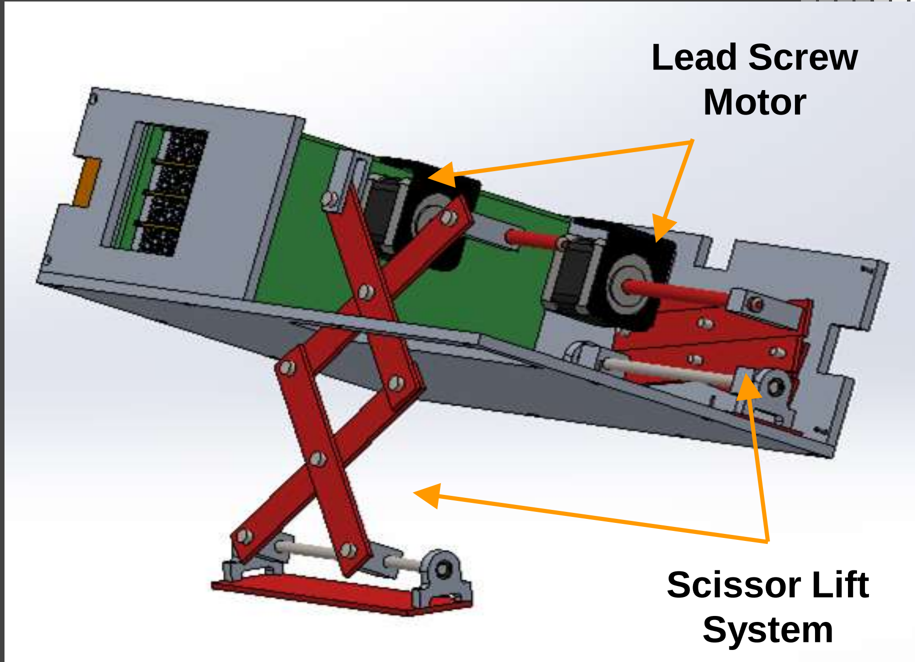
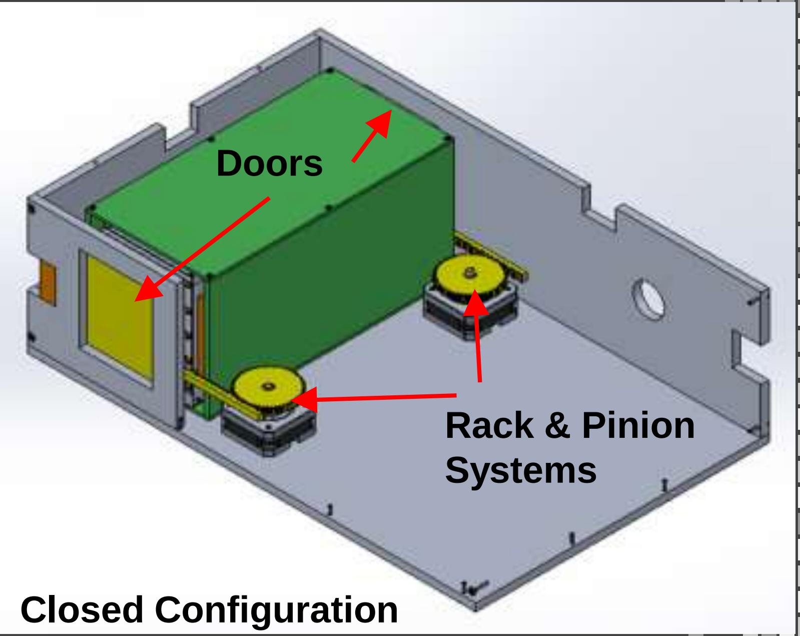


Tilting Mechanism Extended

Door Mechanism

- **Purpose**
  - To protect one side of the instrument from solar wind and expose the other for dust collection
- **Design**
  - Stepper motor
  - Nylon gear and gear rack
  - Aluminum door
- **Current Specs**
  - Door: 9 x 7.5 x 0.32 cm
  - Mass: 0.504 kg



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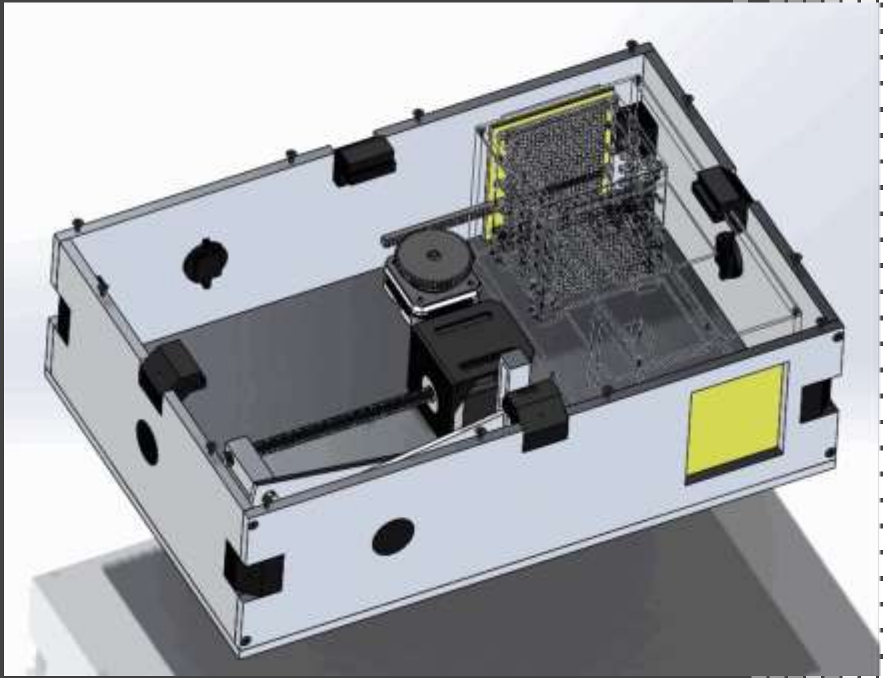
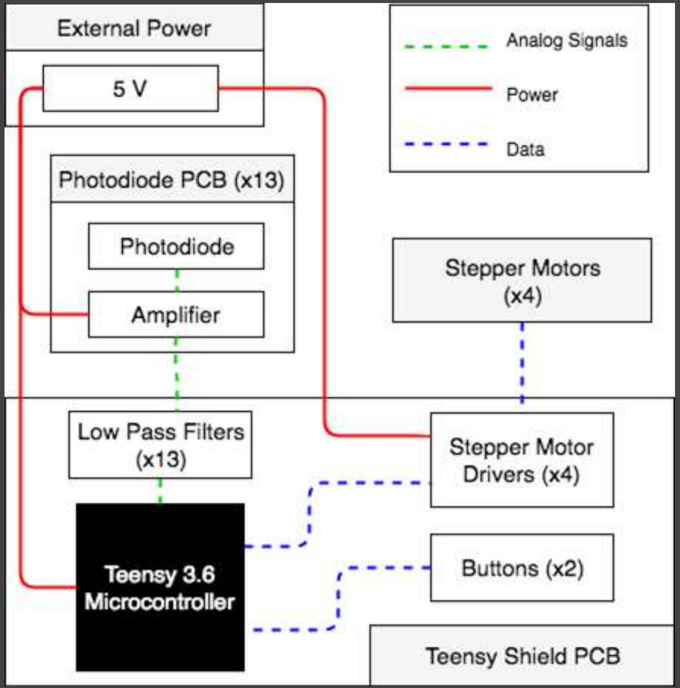


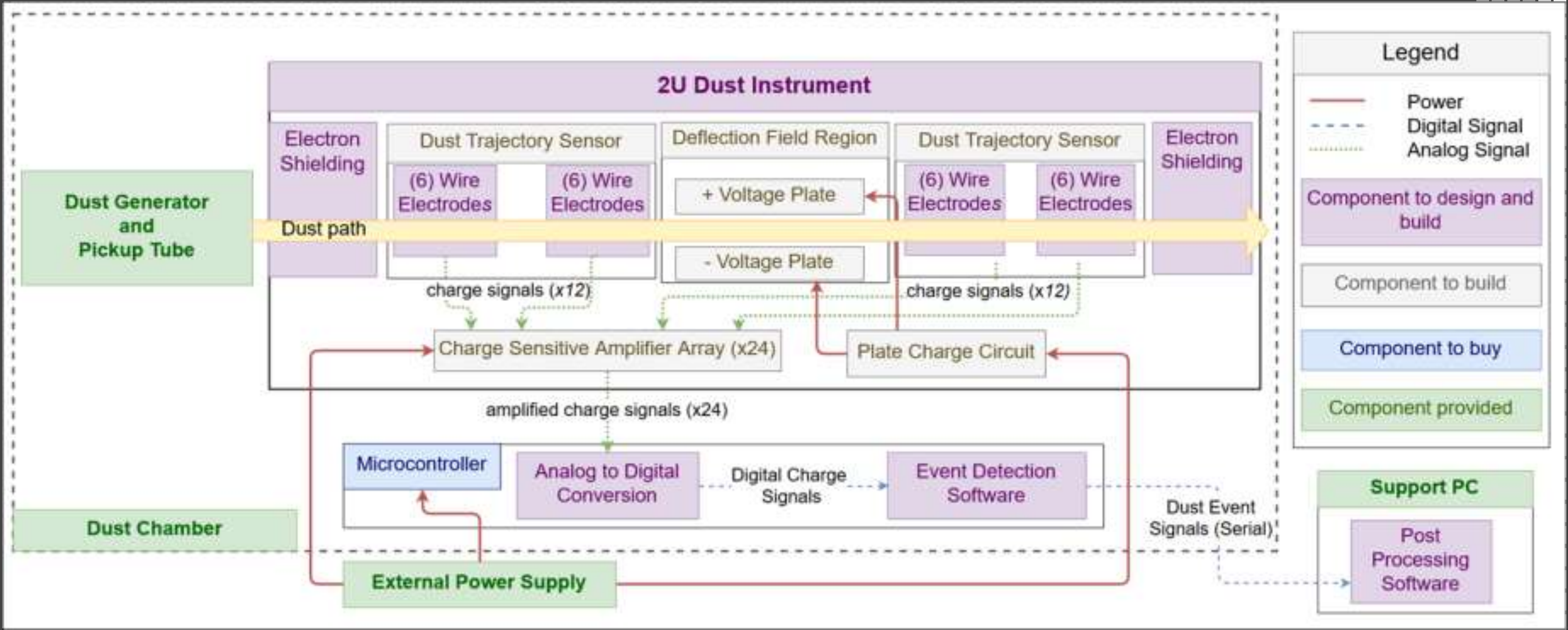
ARS Electronics

- **Purpose**
  - Collect sensor signals
  - Command motors
- **Design**
  - Teensy microcontroller and signal conditioning
  - Custom built PCB to integrate all components
- **Current Specs**
  - 2A limit stepper motor drivers
  - 1Hz sampling of photodiodes

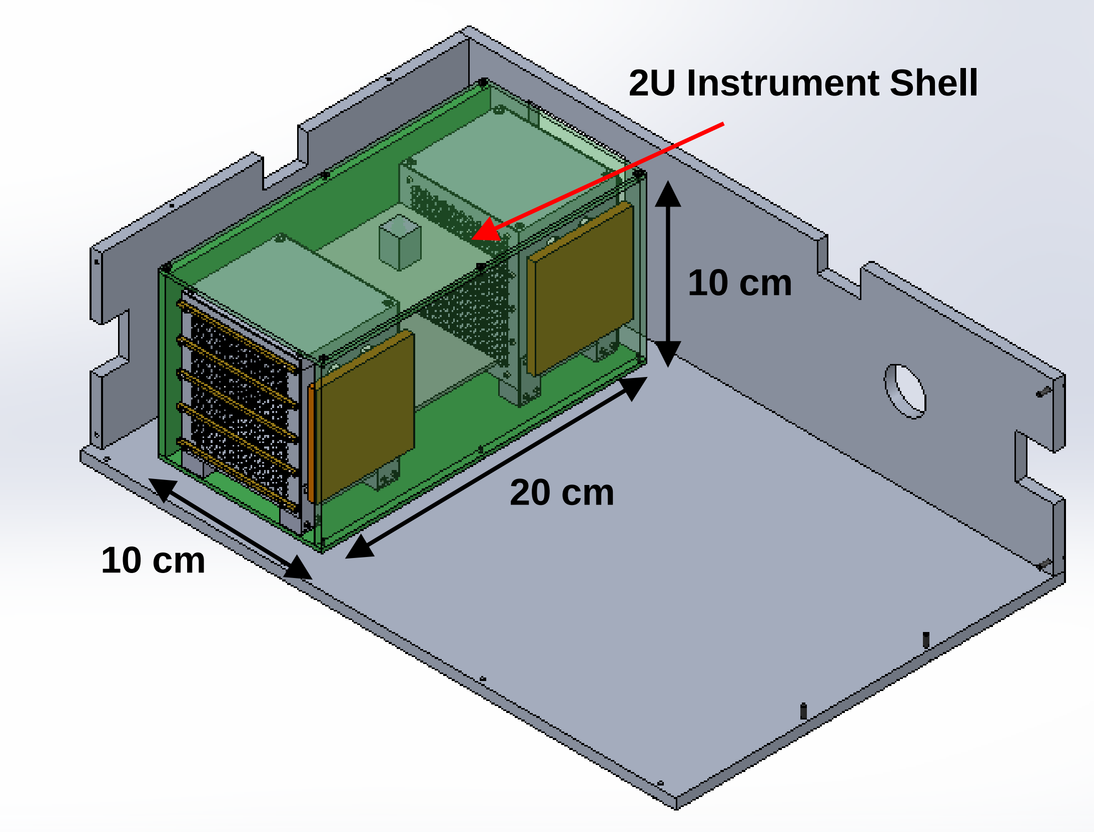


ARS Electronics

Instrument Functional Block Diagram



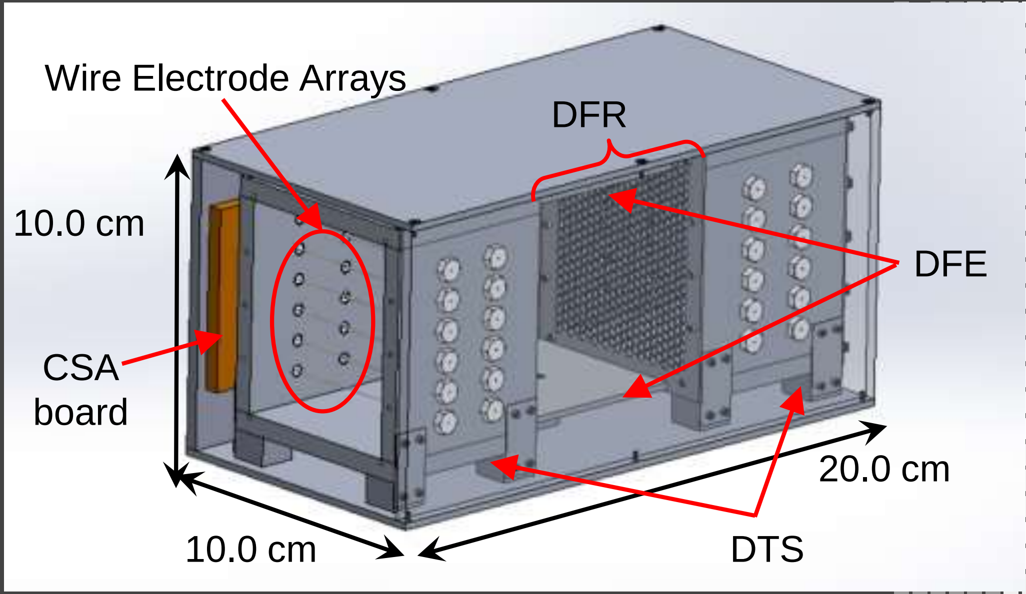
Dust Instrument



Dust Instrument

- **Purpose**
  - Measure charge, mass, and velocity of dust particles
- **Design**

  2U instrument shell containing:
  - Two **Dust Trajectory Sensors (DTS)** with wire electrode arrays
  - Two **Deflection Field Electrode (DFE)** plates on each side of the **Deflection Field Region (DFR)**
  - Two **Charge Sensitive Amplifier (CSA)** boards

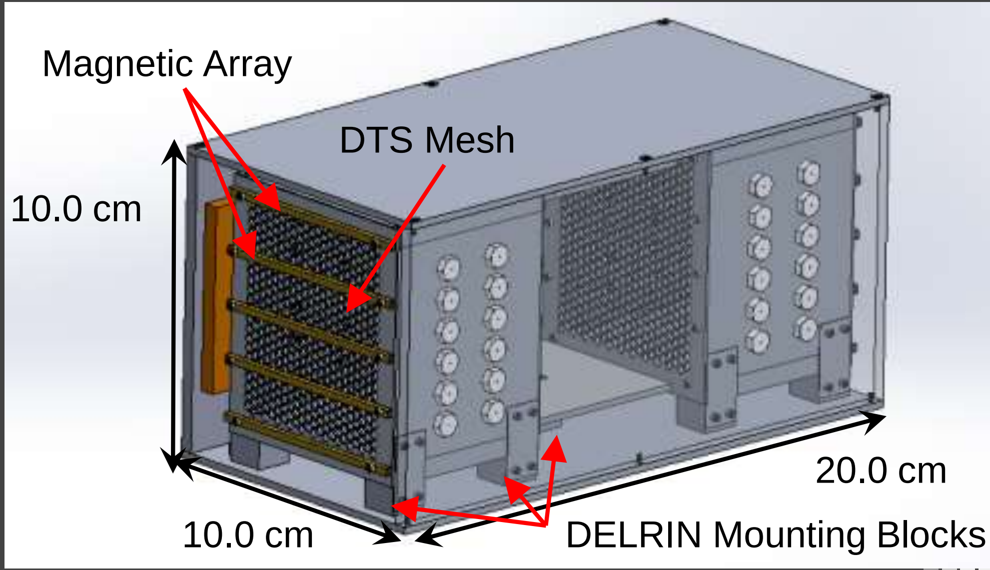


Dust Instrument (Cont.)

- **Design (Cont.)**

  2U instrument shell containing:

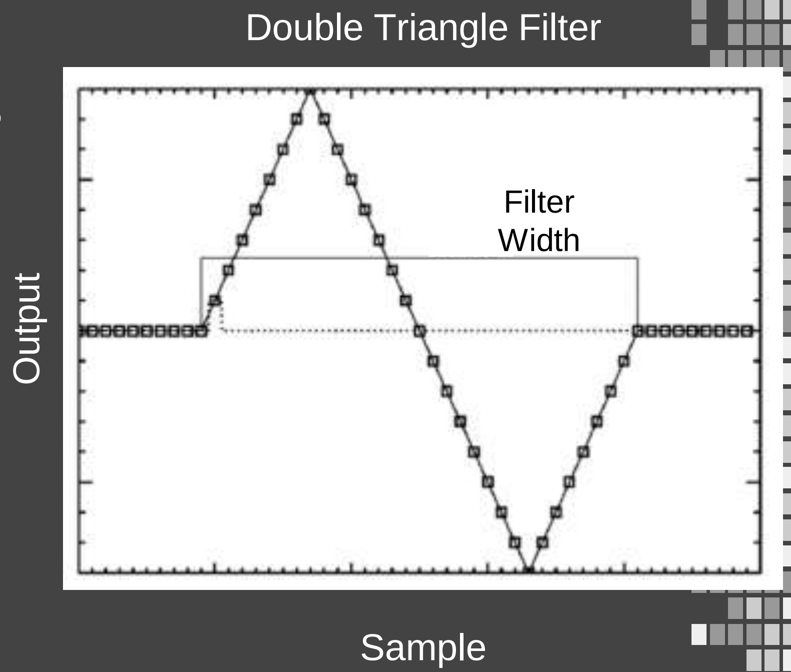
  - A **magnetic array** at the entrance of each DTS to block high energy electrons
  - An **aluminum mesh** at the entrance and exit of each DTS to fully enclose (Faraday Cage)
  - DELRIN **mounting blocks** to electrically isolate DTS and DFE plates from instrument shell



- **Current Specs**
  - Dimensions: 20.0 x 10.0 x 10.0 cm
  - Mass: 1.40 kg (<2.66 kg requirement)

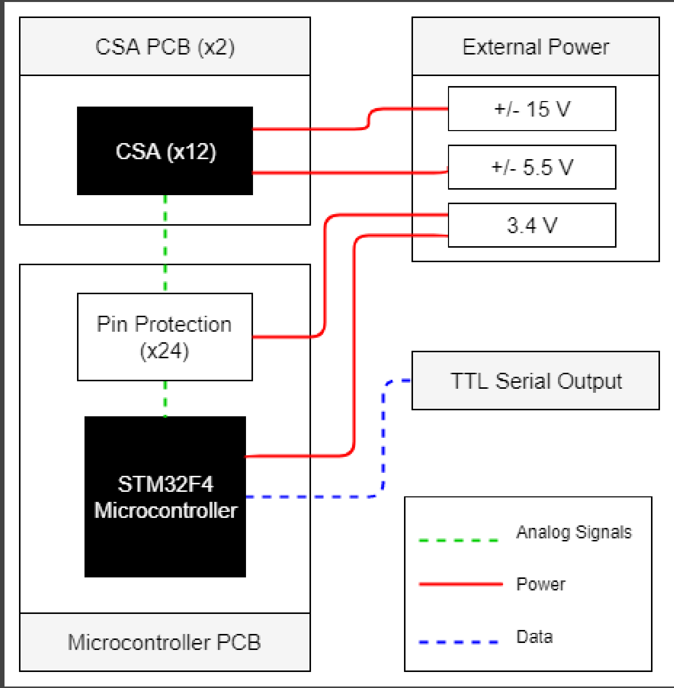
Instrument Software

- **Purpose**
  - Determine when dust particle passes through instrument
  - Extract charge, mass, and velocity values
- **Design**
  - First derivative, non-saturating trigger shape (Double Triangle)
- **Current Specs**
  - Run real time convolution comparison
  - Post processing algorithm to extract desired outputs



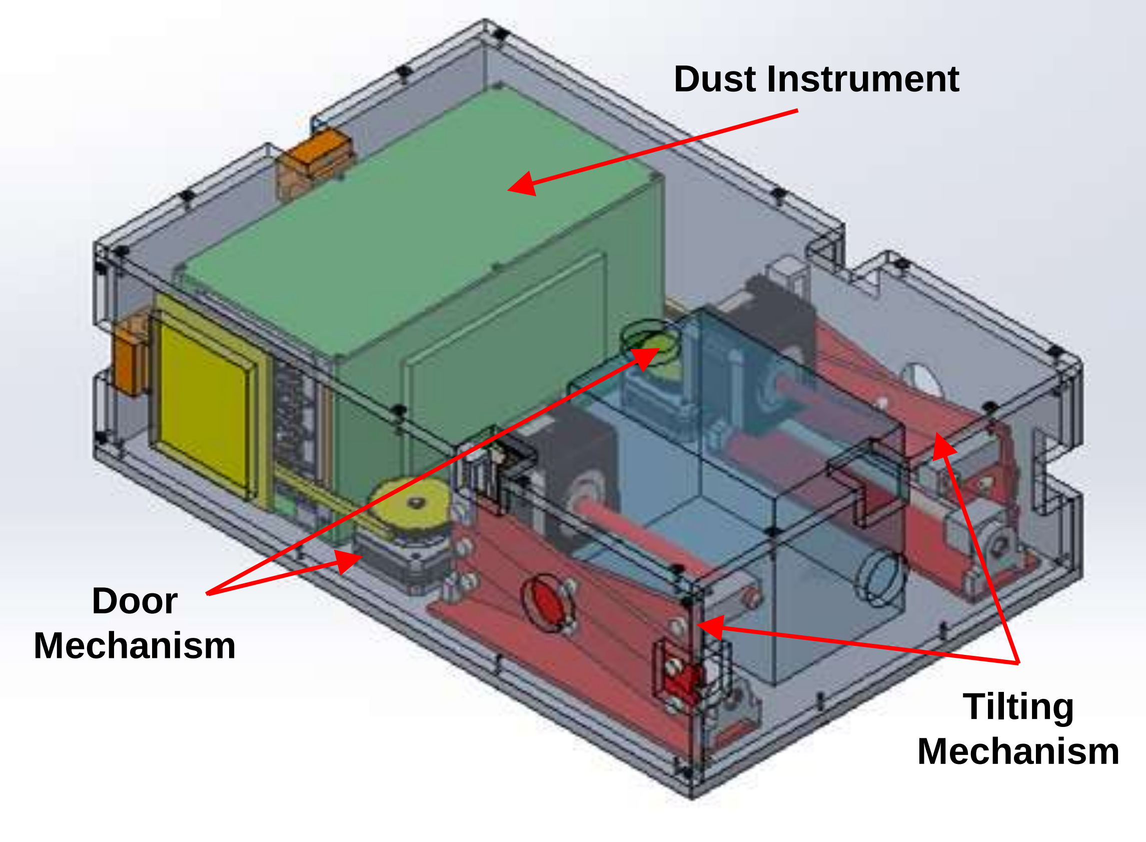
Instrument Electronics

- **Purpose**
  - Amplify dust signal
  - Digitally sample dust signal
- **Design**
  - Array of charge sensitive amplifiers (CSAs)
  - Microcontroller with integrated ADCs
- **Current Specs**
  - 1 kHz CSA sampling



Instrument Electronics

Final Overview

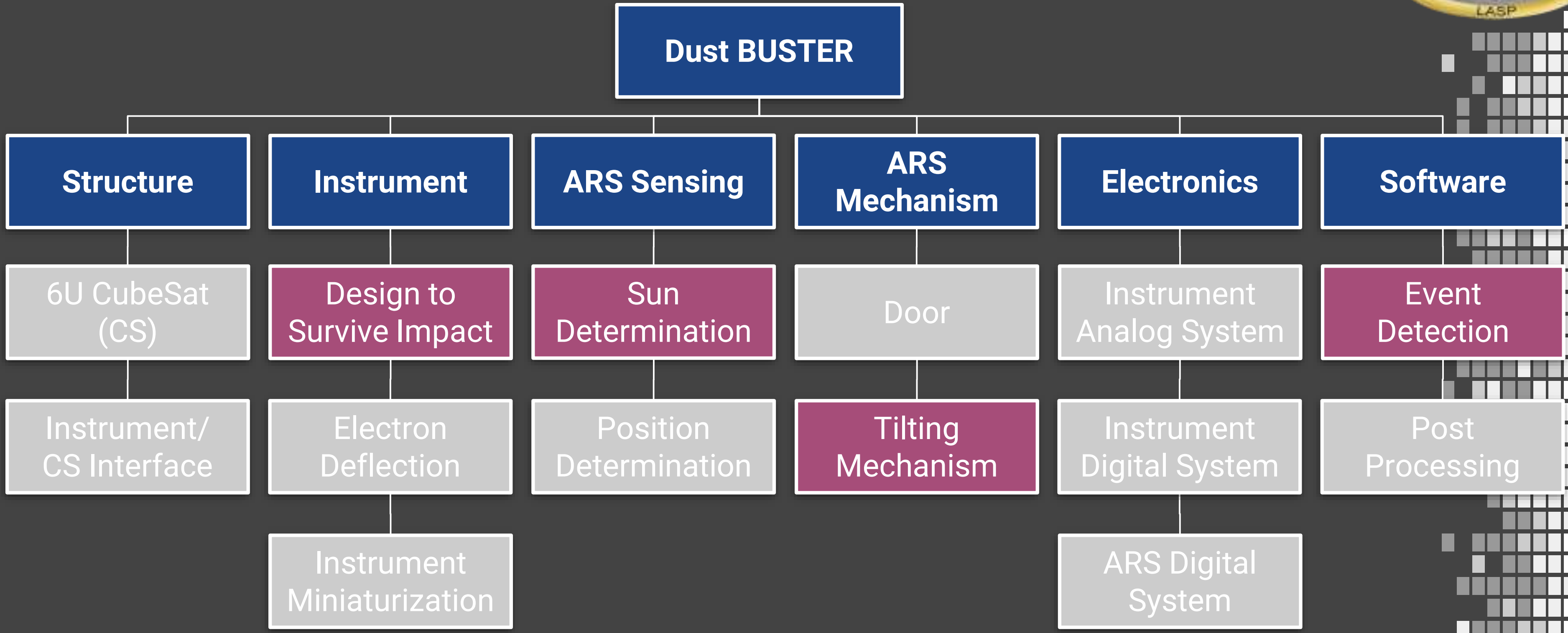


Critical Project Elements

Project Elements

- **Dust BUSTER**
  - **Structure**
    - 6U CubeSat (CS)
    - Instrument/ CS Interface
  - **Instrument**
    - Design to Survive Impact
    - Electron Deflection
    - Instrument Miniaturization
  - **ARS Sensing**
    - Sun Determination
    - Position Determination
  - **ARS Mechanism**
    - Door
    - Tilting Mechanism
  - **Electronics**
    - Instrument Analog System
    - Instrument Digital System
    - ARS Digital System
  - **Software**
    - Event Detection
    - Post Processing

Critical Project Elements



CPEs are in magenta

Critical Project Elements

Critical Project Element	Justification
Surviving Impact	Modeling impact is difficult; limited knowledge
Sun determination	Tight tolerances on parts, complex algorithms
Tilting mechanism	Size and mass restrictions inhibit design options
Real-time event detection	Real-time software design is difficult

Design Requirements and their Satisfaction

Project Purpose

Design Solution

Design Requirements

Project Risks

Verification and Validation

Project Planning

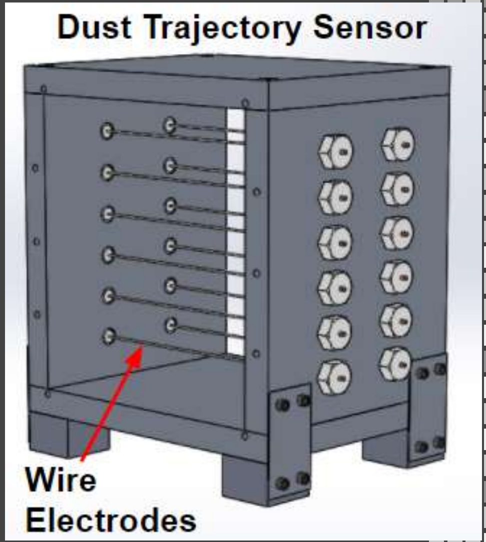
Surviving Impact

Surviving Impact

Specific Requirement:

2.5 - The instrument wire electrodes shall be robust enough to survive crash landing on an asteroid, with Eros as a representative target, withstanding an impulse equal to that generated by the maximum landing velocity of 10 m/s on sand.

"**Survival**" means the wire will not break into pieces and remain attached to the DTS walls



Why?

Customer is concerned about wire electrodes surviving the maximum impact velocity for landing on Eros.

Designs Driven:

- Wire electrode array

Surviving Impact – Design

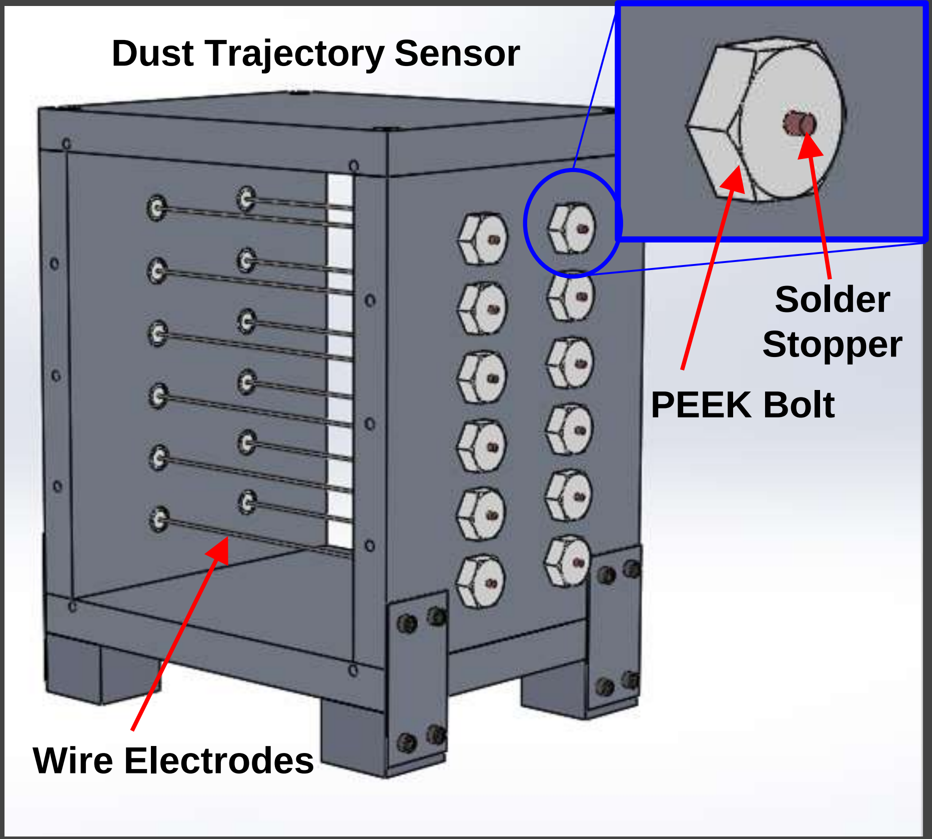
Stainless steel 304 wire electrodes

PEEK plastic threaded bolts

- Electrically isolates wire electrodes

Solder Stopper

- Thicker ball of solder on wire
- Secure wire electrodes axially



Surviving Impact – SW Drop Test

Solidworks Drop Test Sim

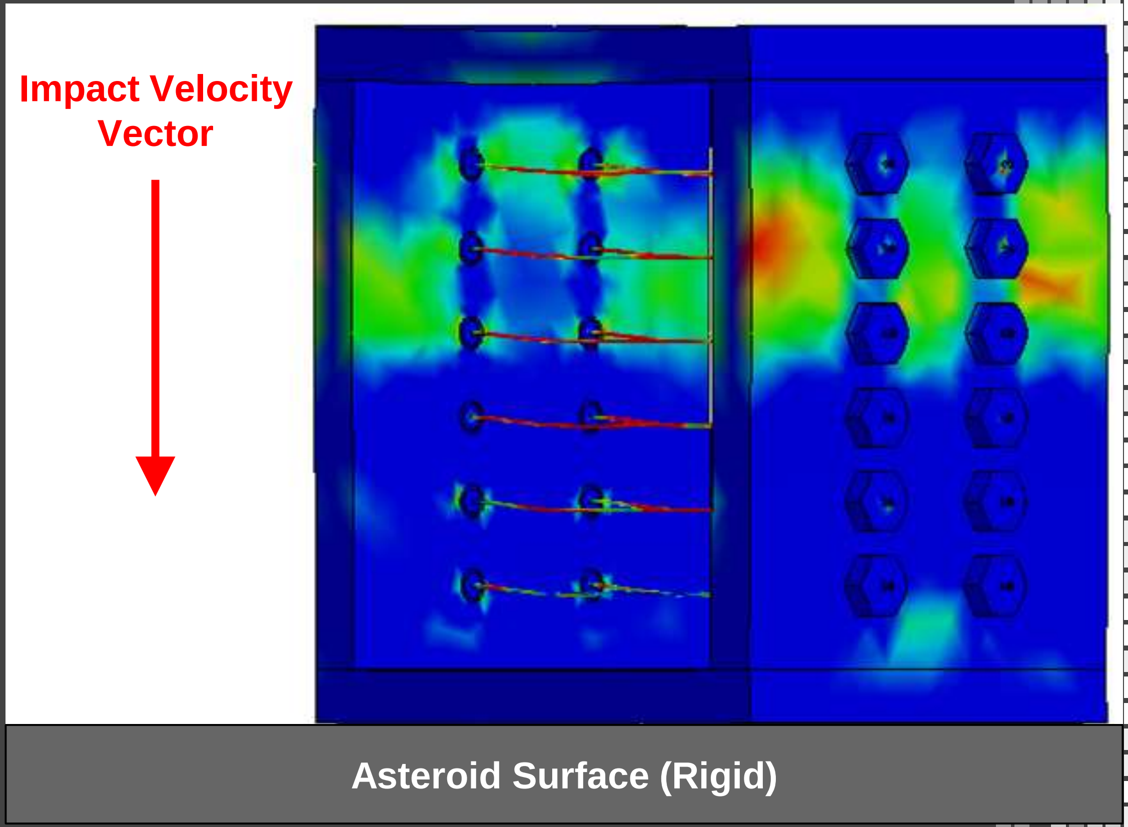
- 10 m/s impact velocity

Assumptions

- Entire DTS is bonded
- Landing on rigid surface
- Perfectly inelastic collision

Purpose

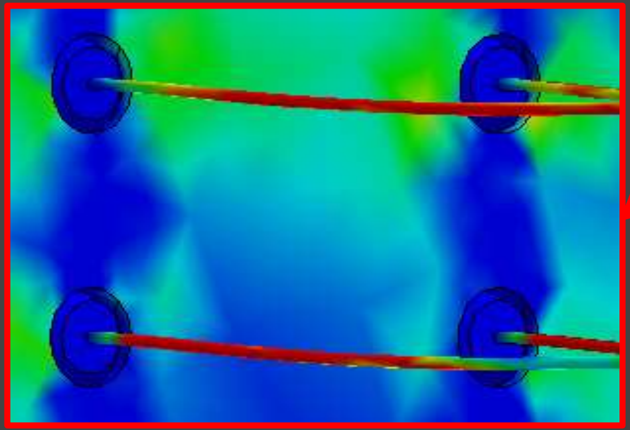
- Determine stress on wire electrode components

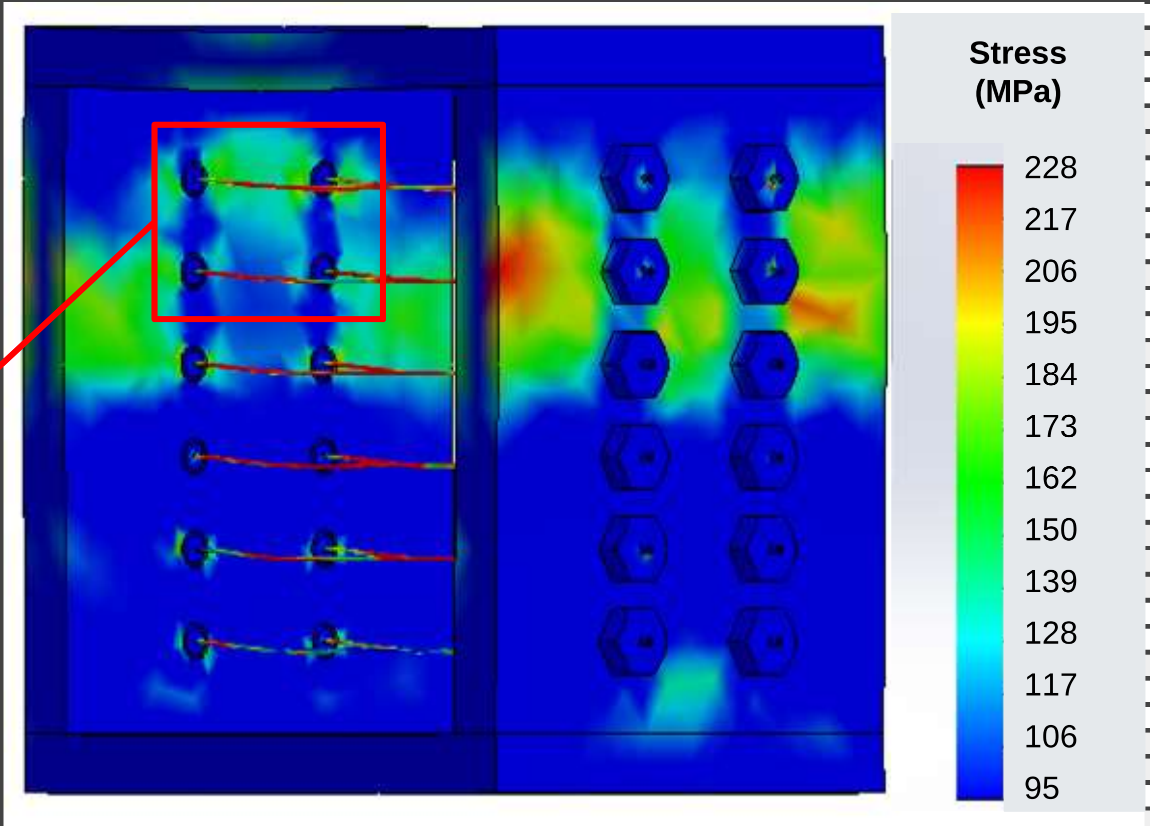


Surviving Impact – SW Drop Test

PEEK plastic threaded bolts

- Max Shear Strength: 95 MPa





Max Bolt Stress: 52.9 MPa

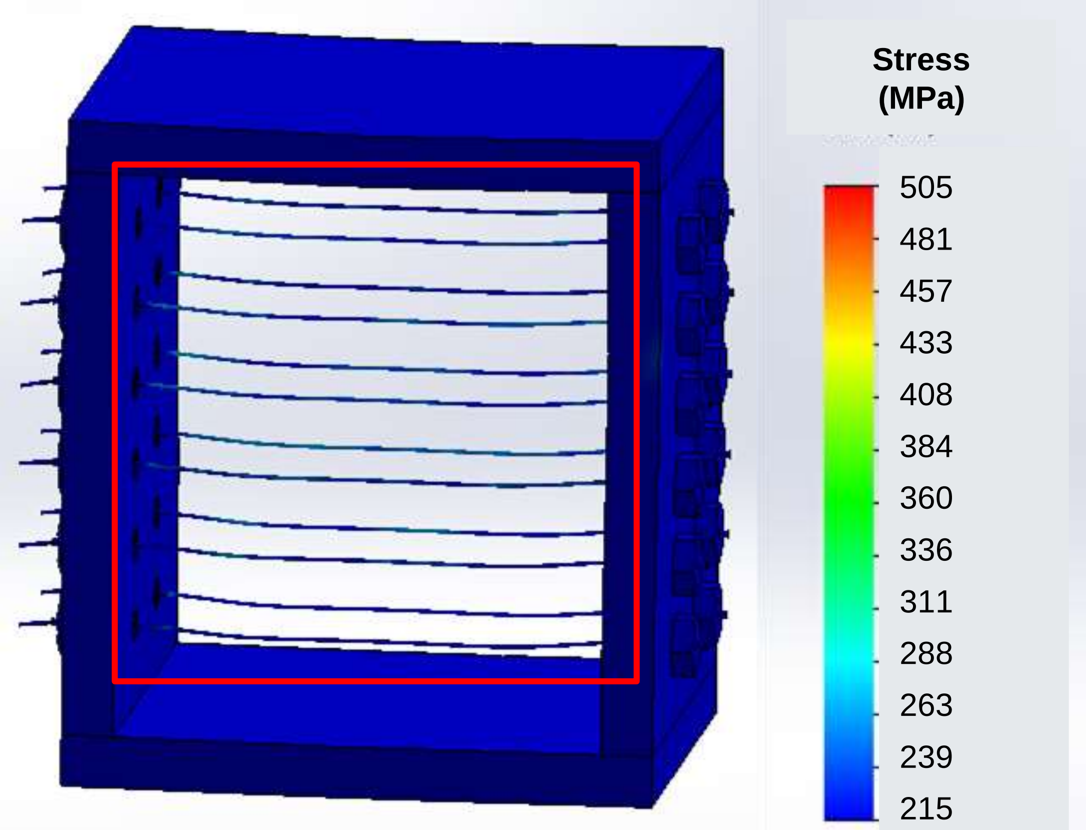
Surviving Impact - Design

Stainless steel 304 wire electrodes

- Ultimate Tensile Strength: 505 MPa

Solder Stoppers

- Length (~ 2.2 mm) designed to shear at 520 MPa normal stress
- Wire will fracture before solder joint shears off



Surviving Impact - Design

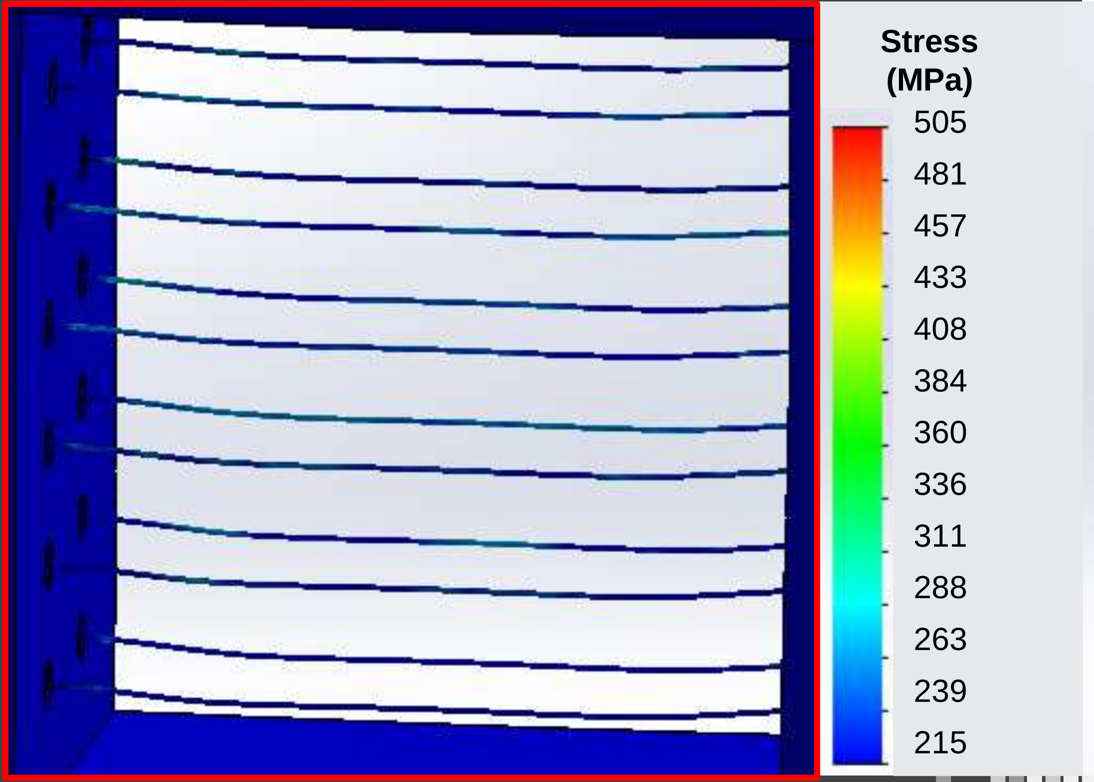
Stainless steel 304 wire electrodes

- Ultimate Strength: 505 MPa

Max Wire Electrode Stress: 272.7 MPa

All components do not exceed their maximum failure stress

Requirement 2.5 satisfied



Sun Determination

Sun Determination Requirement

Specific Requirement:

3.2.4 - The ARS shall maintain full sky view in a 180° half dome over the +Z hemisphere.

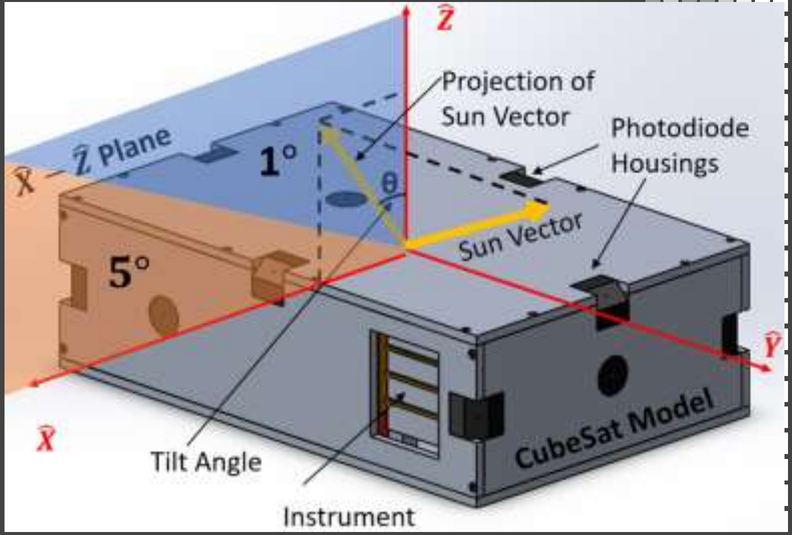
3.2.2 - The ARS shall determine Sun position within ±5° up to 45° above the surface and within ±1 degree from 45° to 90° above the surface, in the XZ plane.

Why?

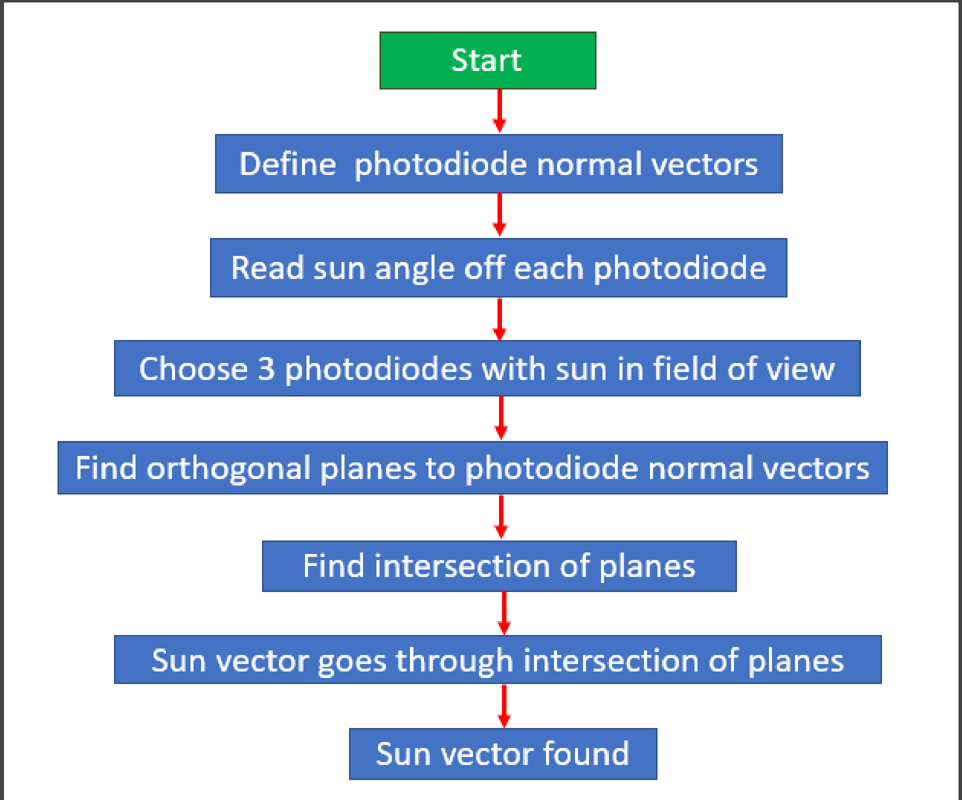
Must actuate CubeSat to 45°, or as close as possible without allowing solar wind to enter instrument

Designs Driven:

- Sun determination algorithm
- Photodiode placement



Sun Finding Algorithm



Full Sky Coverage

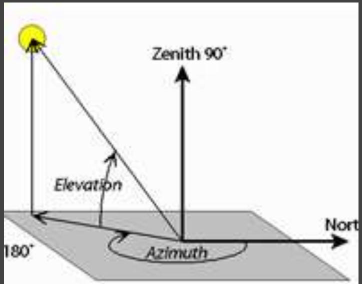
3 measurements required to find sun

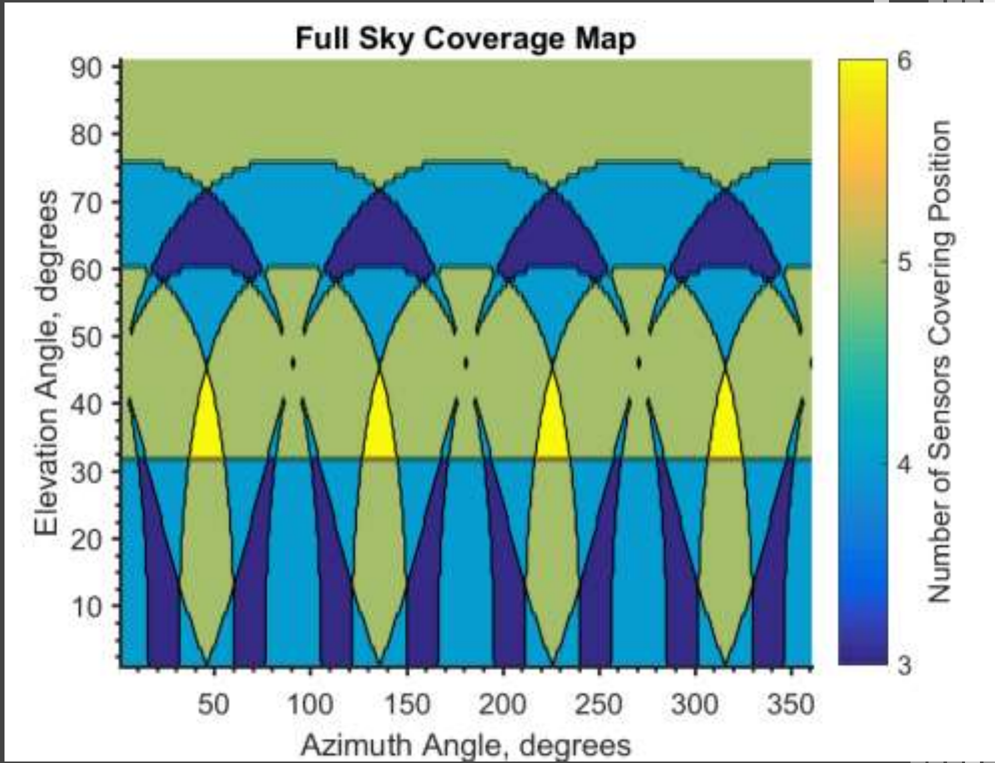
- Full sky must be covered by 3 photodiodes at minimum
- Map shows number of sensors that see each position in the sky

3 Photodiode Minimum

↓

Requirement 3.2.4 satisfied





Full Sky Coverage – Effect of Mounting Errors

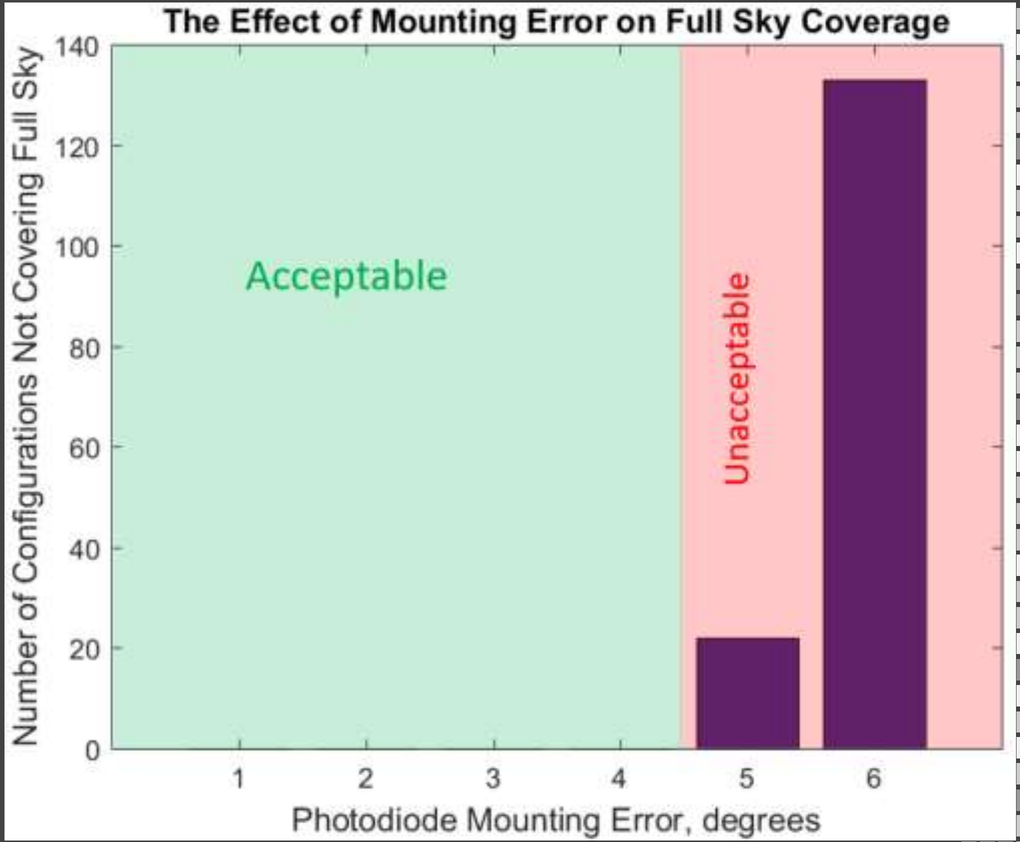
Determine the allowable error in photodiode mounting

- Full sky must be covered by 3 photodiodes at minimum

Varied photodiode mounting randomly with uniform distribution

- 1000 iterations per degree of error

4 degrees of margin in mounting accuracy



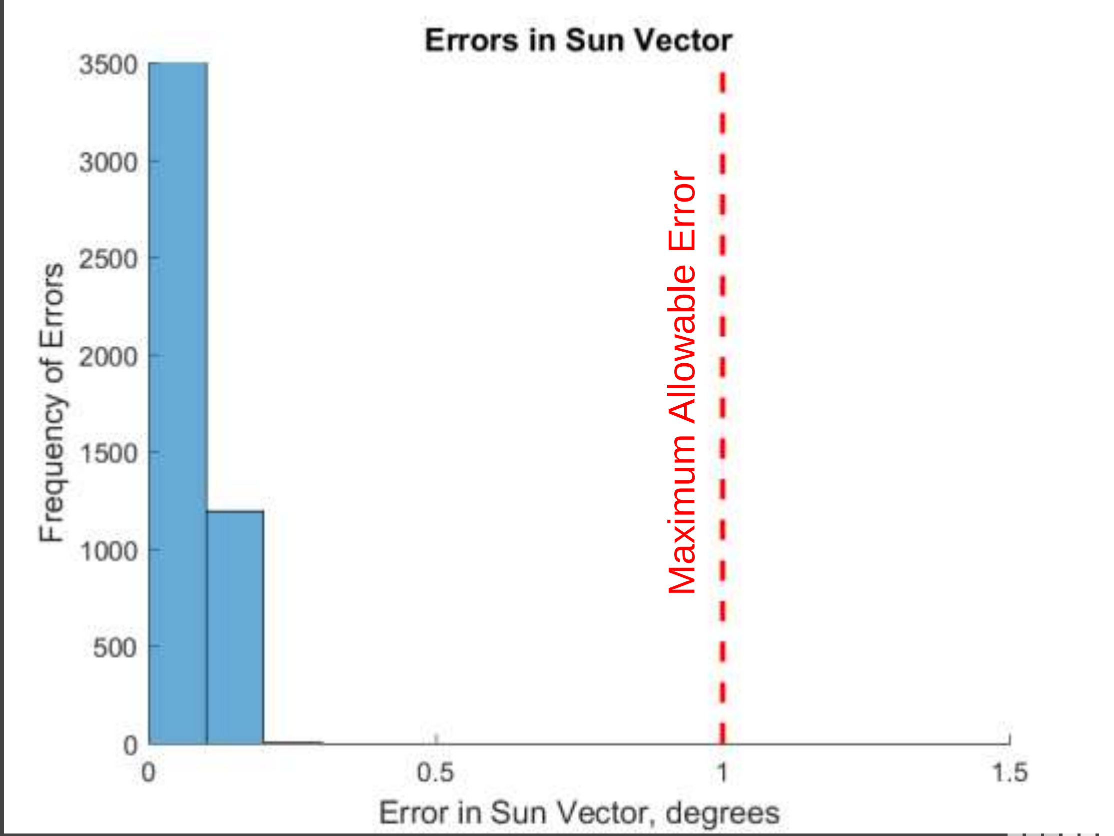
Nominal Design Case

- Varied thermal and sampling noise uniformly
- Move sun vector over full sky
- Maximum error in sun vector is 0.26°

Worst Errors 0.26° < 1°

Requirement 3.2.2 satisfied

- More than 0.9° error margin for > 95% of iterations



Tilting Mechanism

Tilting Mechanism

Specific Requirements:

4.1.2 - The actuators shall tilt the CubeSat up to a maximum 45 degrees one time from the plane of the ground

4.1.2.1 - The actuators shall be able to tilt the CubeSat to 1 degree increments with an accuracy of ± 0.5°

Why?

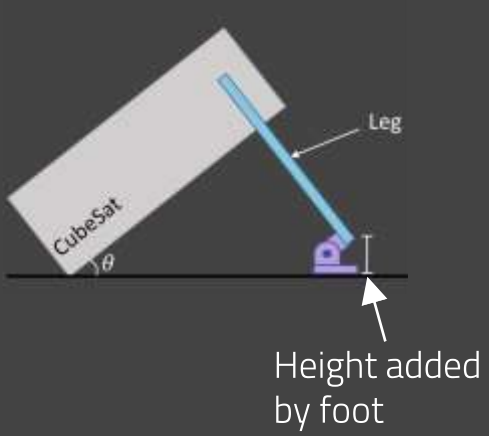
45° is customer specified as optimal angle for science data collection. Need 1° resolution to achieve max tilt without putting instrument in the sun.

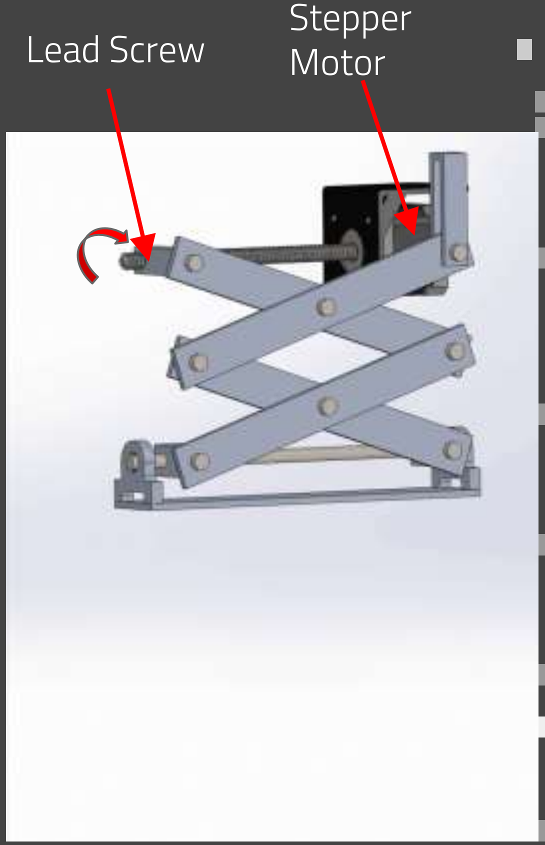
Design Driven:

- Fit within 3U of remaining CubeSat volume
- Actuator type

Tilt Mechanism in Action

- Model accounts for:
  - Height added by the foot
  - Leg internal to CubeSat
- **Max tilt angle is 49.12°**
  - Based on maximum distance that legs can deploy





Max Tilt > 45°

Requirement 4.1.2 satisfied

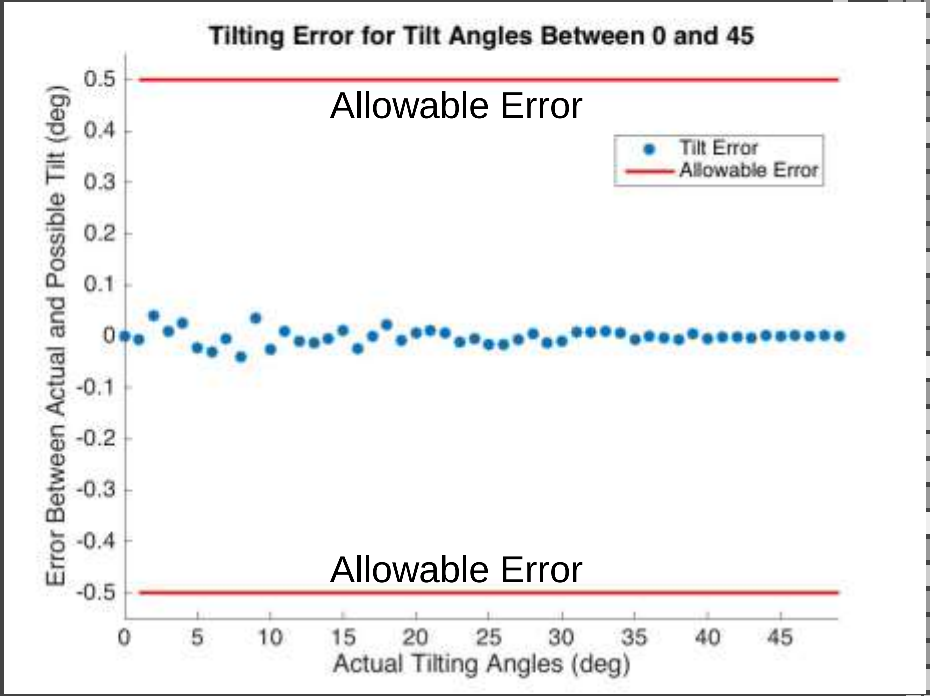
Tilting Mechanism Error

Determine possible tilt for each step

- Tilt angle calculated for each leg length that could be achieved per motor step
  - Error is difference between ideal 1 degree increments and closest achievable tilt
- Error is allowable at all tilts

Max error 0.04° < 0.5°

Requirement 4.1.2.1 satisfied



Real-Time Event Detection

Instrument - Event Detection

Specific Requirement

6.3.2 - The software shall detect dust events in real-time using a stable filter design.

Why?

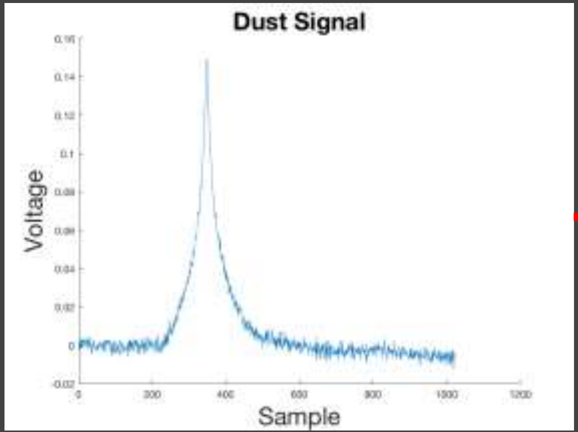
Only want to output data when a dust event happens

Designs Driven:

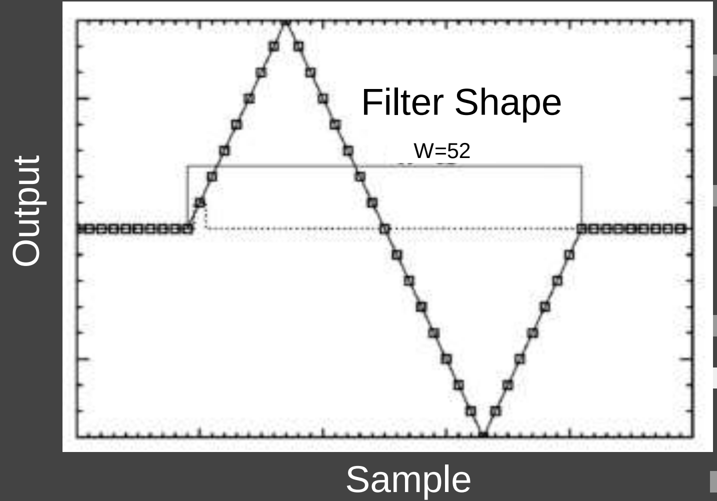
- Dust event data compared to filter of known shape using simple convolution algorithm
- Dust event triggered when a desired output threshold is met
- Use LASP Flight Software framework to aid in real-time software design

Real-Time Event Detection

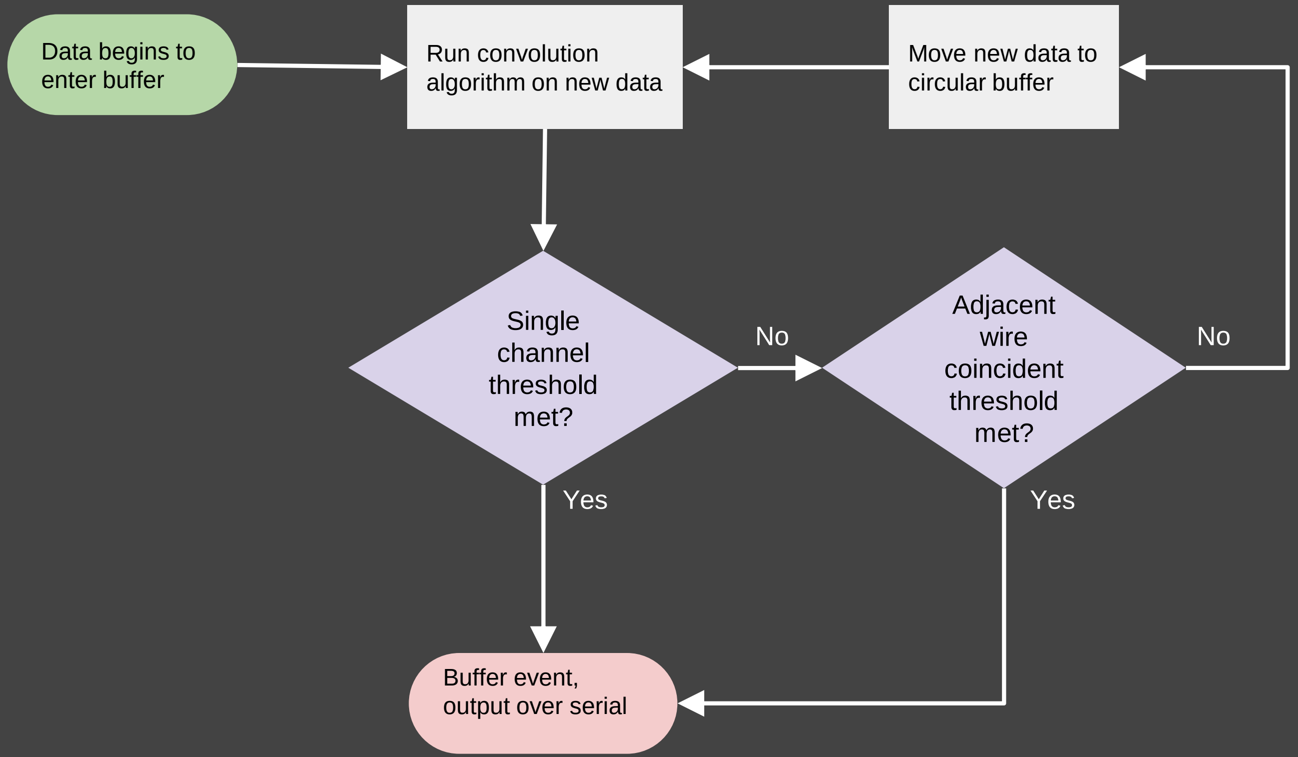
- Output of filter: $Y[n] = 2Y[n-1] - Y[n-2] + X[n] - 2X[n-W/4] + 2X[n-3W/4] - X[n-W]$
  - Y is the output of the filter (initialized as zeros)
  - X is the dust data point
- Filter shape is a non-saturating, double triangle which resembles the shape of dust events
- Threshold is based on a scalar multiple of the maximum noise and is calibrated continuously



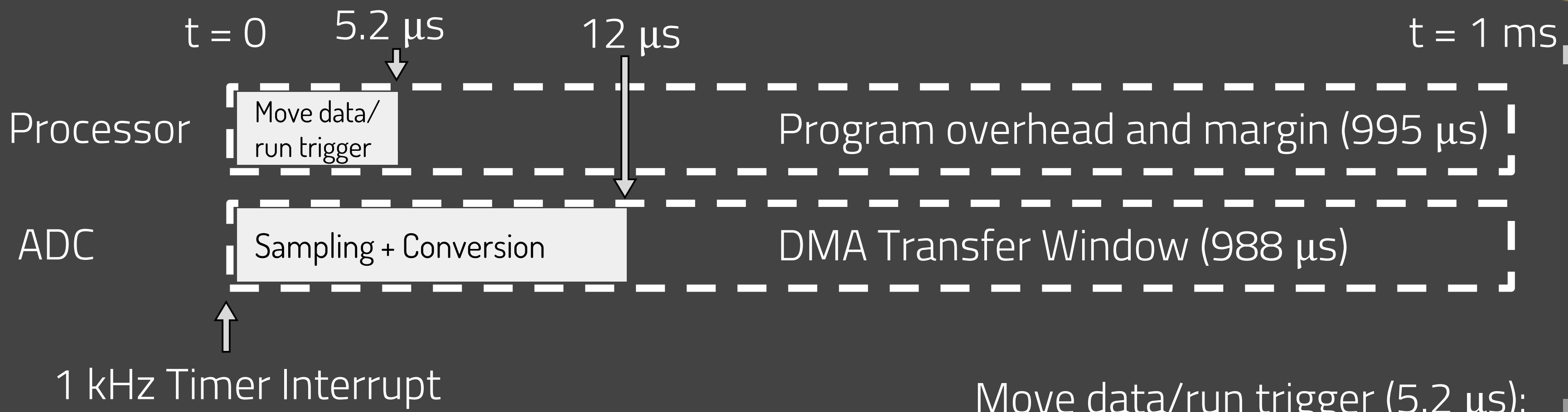
Compared With



Real-Time Flow Diagram



Instrument - Real-Time Software



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

Project Risks

Project Purpose
Design Solution
Design Requirements
Project Risks
Verification and Validation
Project Planning

Risk Descriptions

Risk	Description	Likelihood	Severity	Total
INT-4	Can only test full dust instrument in vacuum	5	5	25
INST-2	Don't have past test data	5	4	20
ELEC-1	Need to remake PCB	4	4	16
MECH-1	Mechanism mounting errors	4	4	16
ARS-1	Photodiode noise	4	4	16
ARS-6	Inconsistencies in photodiode apertures	4	4	16
ELEC-4	Noise from connections and EMI	3	5	15
STRUCT-2	Wire electrode does not survive impact	4	3	12

Highest Risks

		Severity				
		1	2	3	4	5
Likelihood	5				INST-2	INT-5
	4			STRUCT-2	ELEC-1, MECH-1 ARS-1, ARS-6	
	3					ELEC-4
	2					
	1					

Legend							
(green)	Low (1-3)	(yellow)	Moderate (4-9)	(orange)	High (10-15)	(red)	Extreme (16-25)

Mitigation Strategies

Risk	Effect	Mitigation Strategy
INT-4	Won't know if instrument works until vacuum testing	Modular test plan for all components building up to integration
INST-2	Must test software without real data	Modular code design; create simulated data
ELEC-1	PCB remake uses schedule margin	Schedule in remake; get designs reviewed
MECH-1	Mis-mounted moving parts slip or lock	Check acceptable tolerances while machining
ARS-1	Can't detect sun due to noise	Add filters to photodiode circuits
ARS-6	Errors in sun position due to manufacturing	Calibration for mounting and machining error, calculate acceptable error
ELEC-4	Can't detect dust signals above noise	Minimize noise and EMI in instrument circuit
STRUCT-2	Fail impact requirement	Solidworks drop test; characterize failure

Mitigation Impact on Risks

		Severity				
		1	2	3	4	5
Likelihood	5			INST-2, INT-5		
	4		ARS-6			
	3		ELEC-1	STRUCT-2		
	2				MECH-1, ARS-1	ELEC-4
	1					

Legend							
(green)	Low (1-3)	(yellow)	Moderate (4-9)	(orange)	High (10-15)	(red)	Extreme (16-25)

Verification and Validation

Verification Plan

Component Tests
Jan 16th - Mar 5th

- Verify Sensitivities
  - Photodiode
  - Accelerometer
- Verify Tolerances
  - 3D Printed Parts
  - Machined Parts
- Verify PCBs
  - CSA
  - DTS
- Verify Software

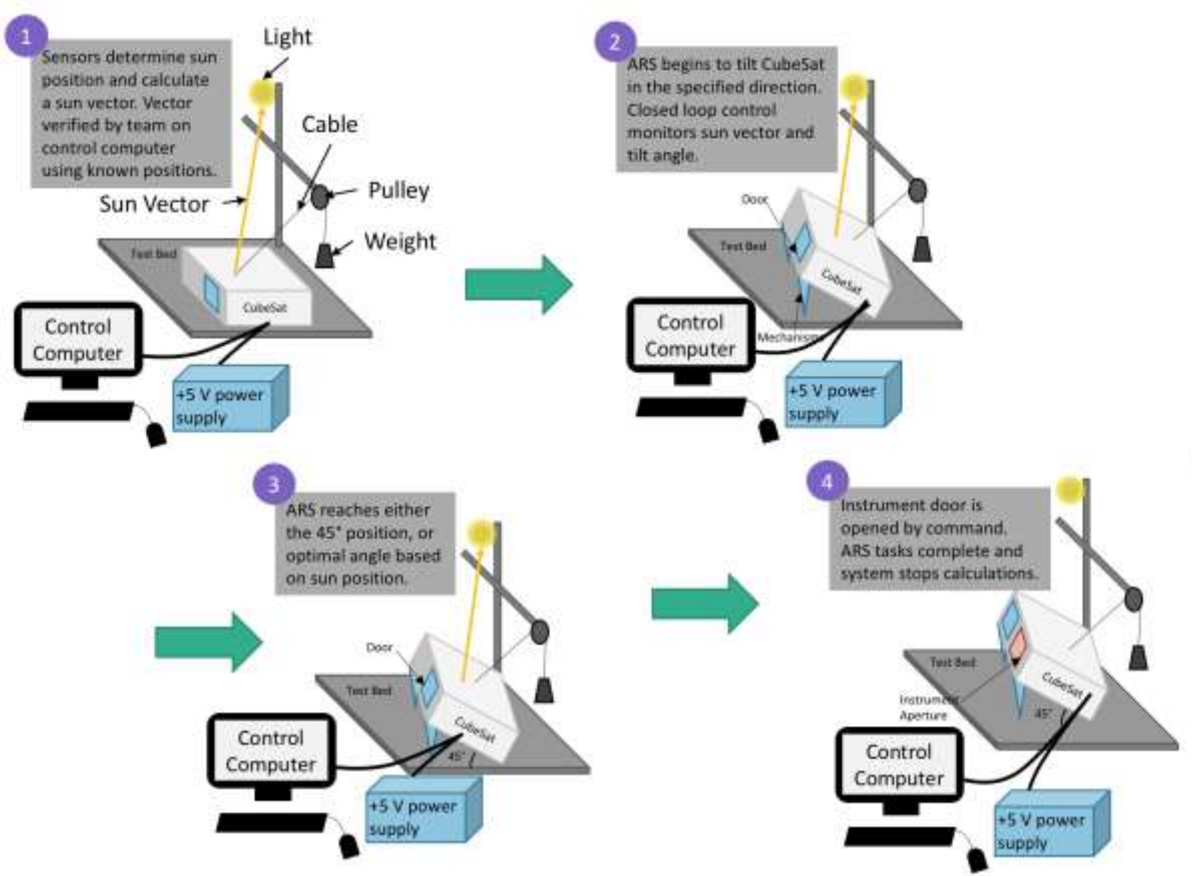
Subsystem Tests
Mar 5th - Mar 19th

- CubeSat Model
- ARS
  - ARS Sensors
  - ARS Tilt Mechanism
  - ARS Door Mechanism
- Instrument
  - Impact Test
  - Circuit Test

Systems Tests
Mar 19th - Apr 16th

- Instrument
  - Electron Shield
  - Trigger
  - Post-Processing Software
- ARS Test
  - Closed Loop System

ARS System Level Test

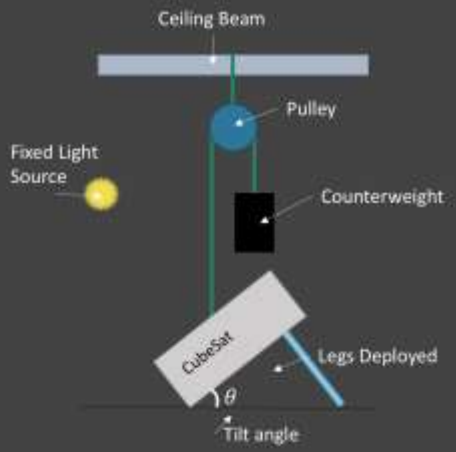


Equipment Needed	Procurement
5V Power Supply	Borrowed
Light Source	QB50
Computer	Owned
Pulley, Cord, Weight	Buy

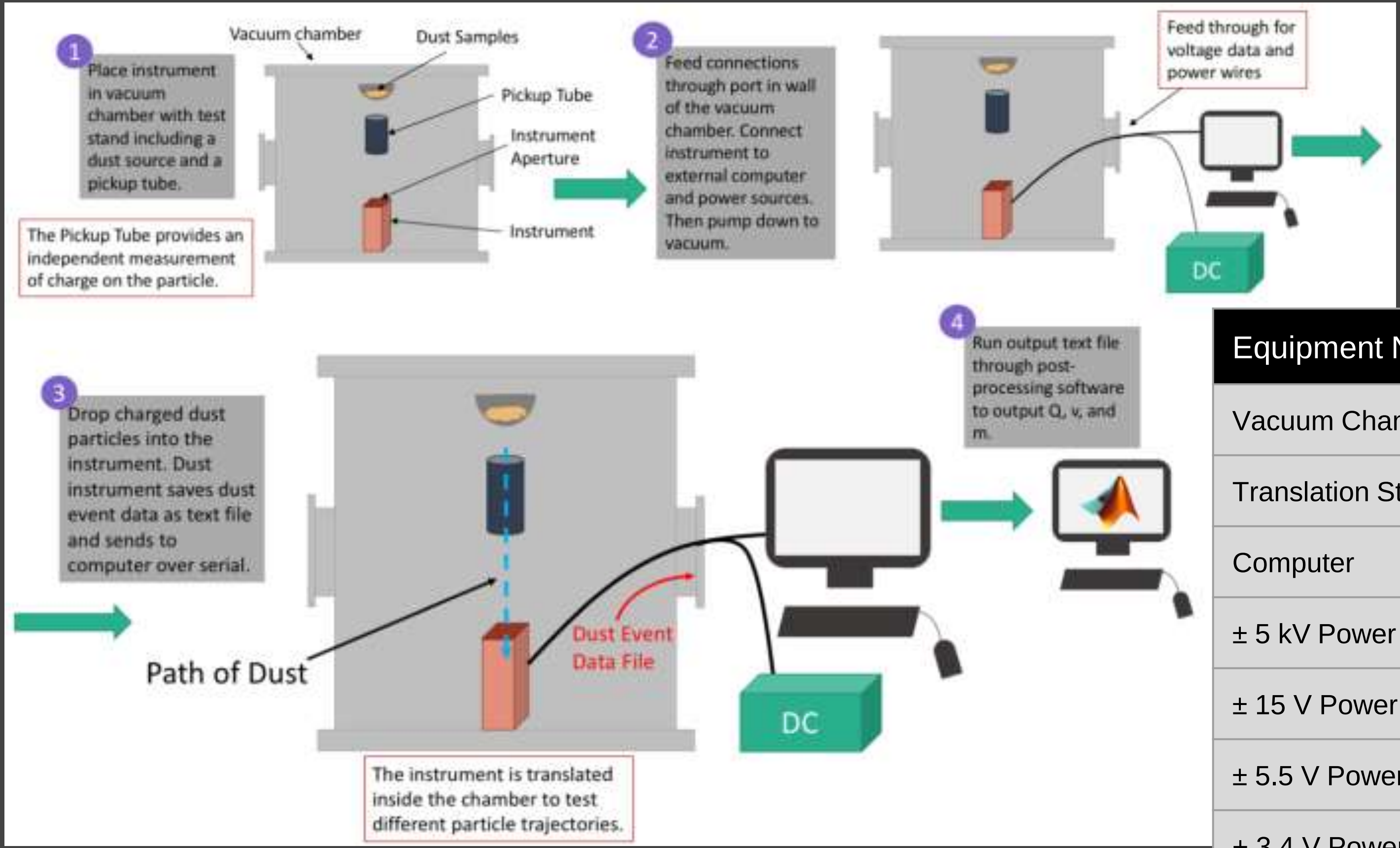
ARS System Level Test

Objective	• **Determine light's location** and **tilt the CubeSat** to the angle calculated by the ARS software with **closed-loop control** • Compare software outputs to known light location • Compare measured tilt angle (from accelerometer) to the calculated angle to verify that the motor has tilted the correct number of steps • Software determines which door to open, and door opens on command
Location	Senior Projects Depot
FR Verified	FR3: Open the instrument door that is pointing away from the sun. FR4: The shaded side is tilted FR5: CubeSat tilts 45°or optimal amount FR6: The software run ARS algorithms.

Data Needed	Required Resolution	Compared to
Photodiode Sun Vector	1°	Actual Sun Vector
Commanded Motor Tilt Angle	0.5°	Model Tilt Angle
Accelerometer Tilt Angle	0.5°	Actual Tilt Angle



Instrument System Level Test



Equipment Needed	Procurement
Vacuum Chamber	IMPACT Lab
Translation Stage	IMPACT Lab
Computer	IMPACT Lab
± 5 kV Power Supply	IMPACT Lab
± 15 V Power Supply	IMPACT Lab
± 5.5 V Power Supply	IMPACT Lab
+ 3.4 V Power Supply	IMPACT Lab

Instrument System Level Test

IMPACT Lab
Vacuum Chamber

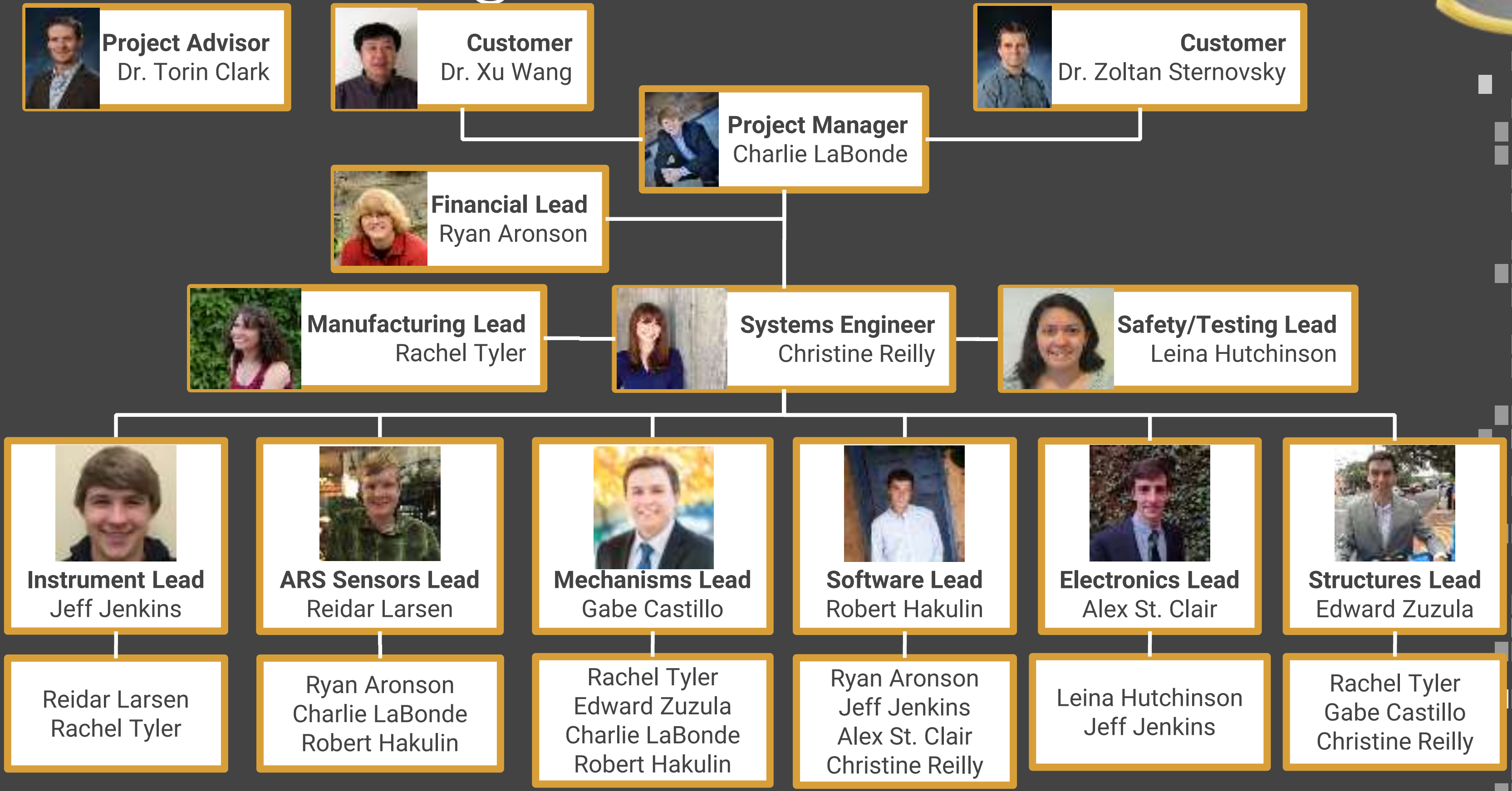
Objective	• Verify that instrument detects a dust event successfully • Verify ADC sampling rate is 1 kHz • Compare post-processing results (particle **charge**, **mass**, and **velocity**) to expected values
Location	IMPACT Dust Lab (walk-in availability)
FR Verified	FR2: The instrument shall detect dust particles that enter the instrument. FR5: The electronics process dust signals in real time FR6: The software can detect events and calculate results

Data Calculated	Compare to	Expected Range
Charge	Pickup tube calculation	8-160 fC
Mass	Average known particle mass	10-50 µg
Velocity	Average velocity given gravitational acceleration	1-2 m/s

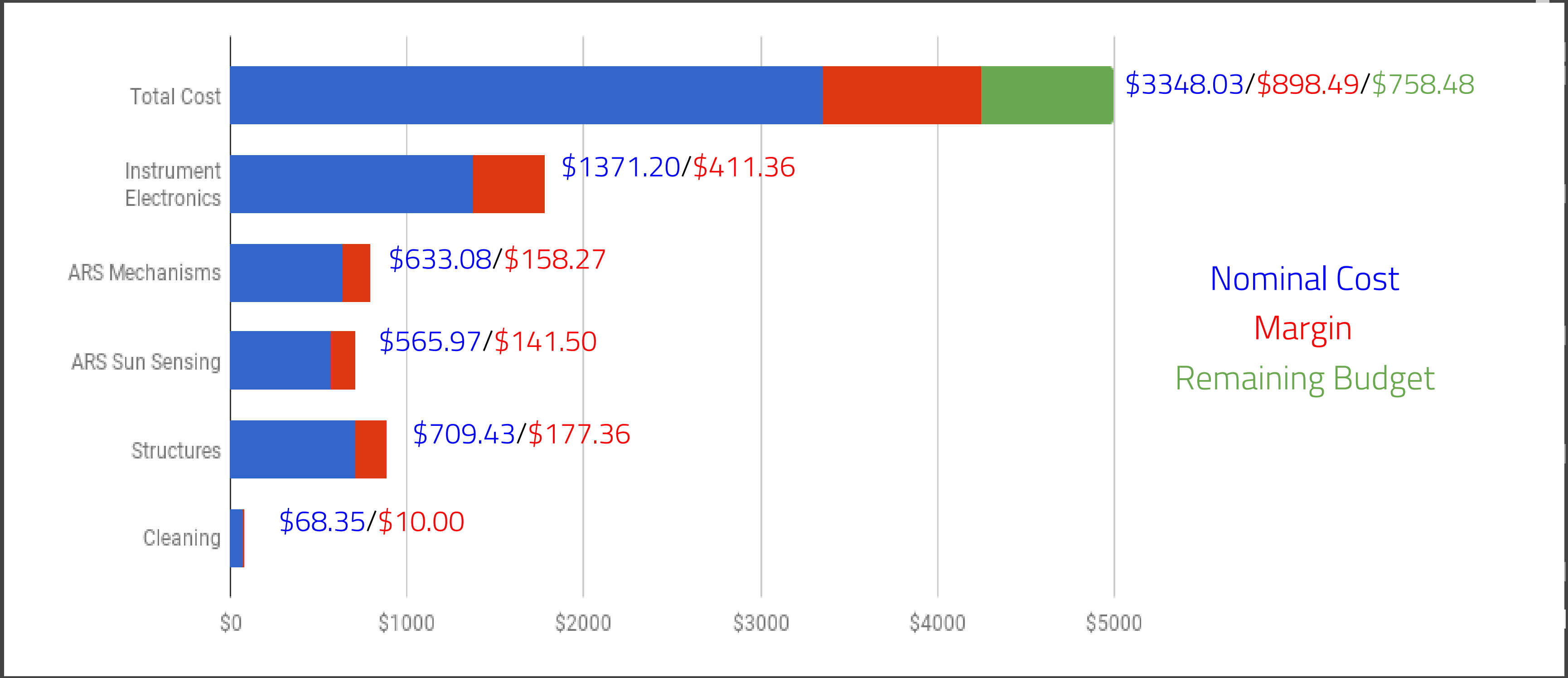
Project Planning

Project Purpose → Design Solution → Design Requirements → Project Risks → Verification and Validation → Project Planning

Organizational Chart



Cost Plan

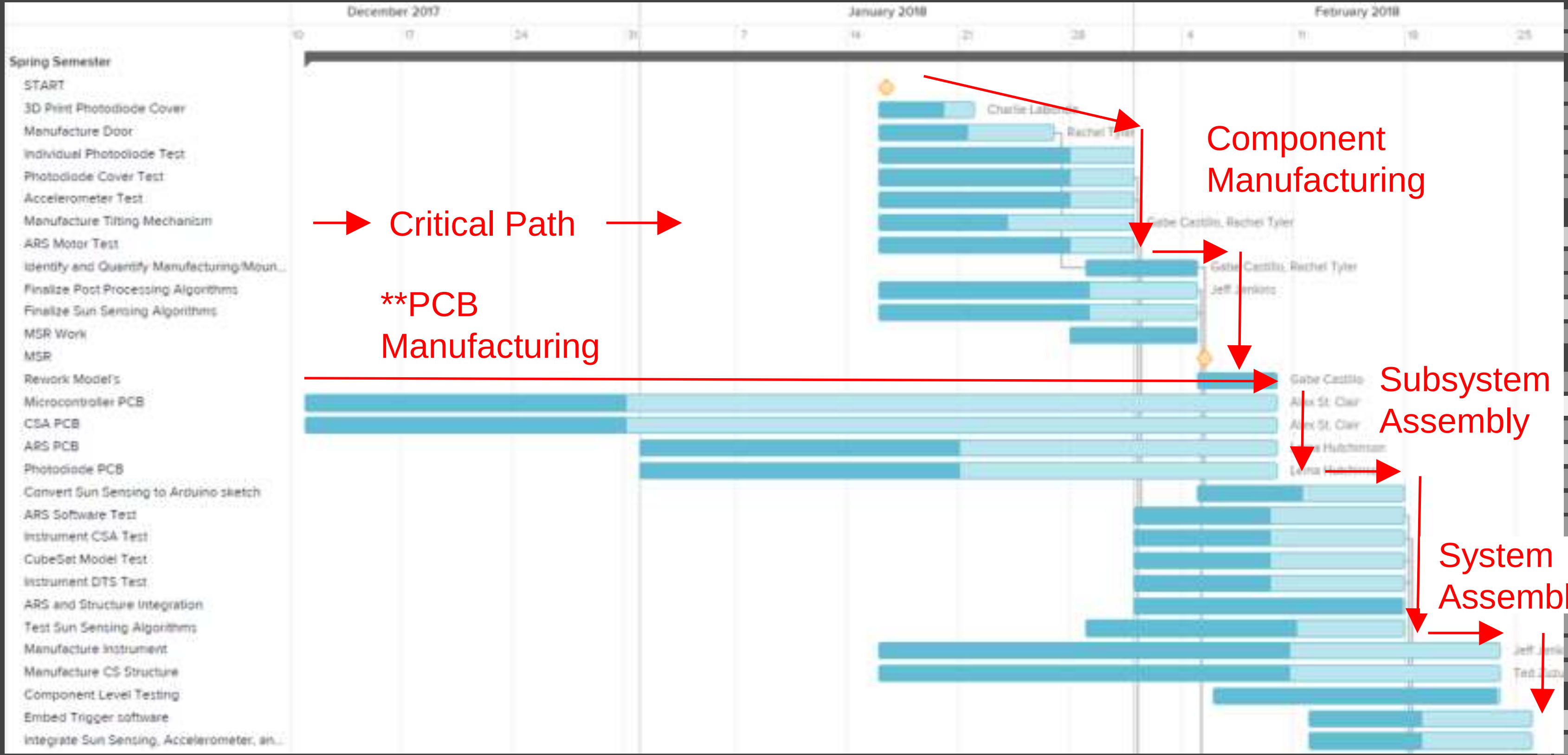

Total Cost
Instrument Electronics
ARS Mechanisms
ARS Sun Sensing
Structures
Cleaning
$3348.03/$898.49/$758.48
$1371.20/$411.36
$633.08/$158.27
$565.97/$141.50
$709.43/$177.36
$68.35/$10.00
$0
$1000
$2000
$3000
$4000
$5000
Nominal Cost
Margin
Remaining Budget

Work Breakdown Structure

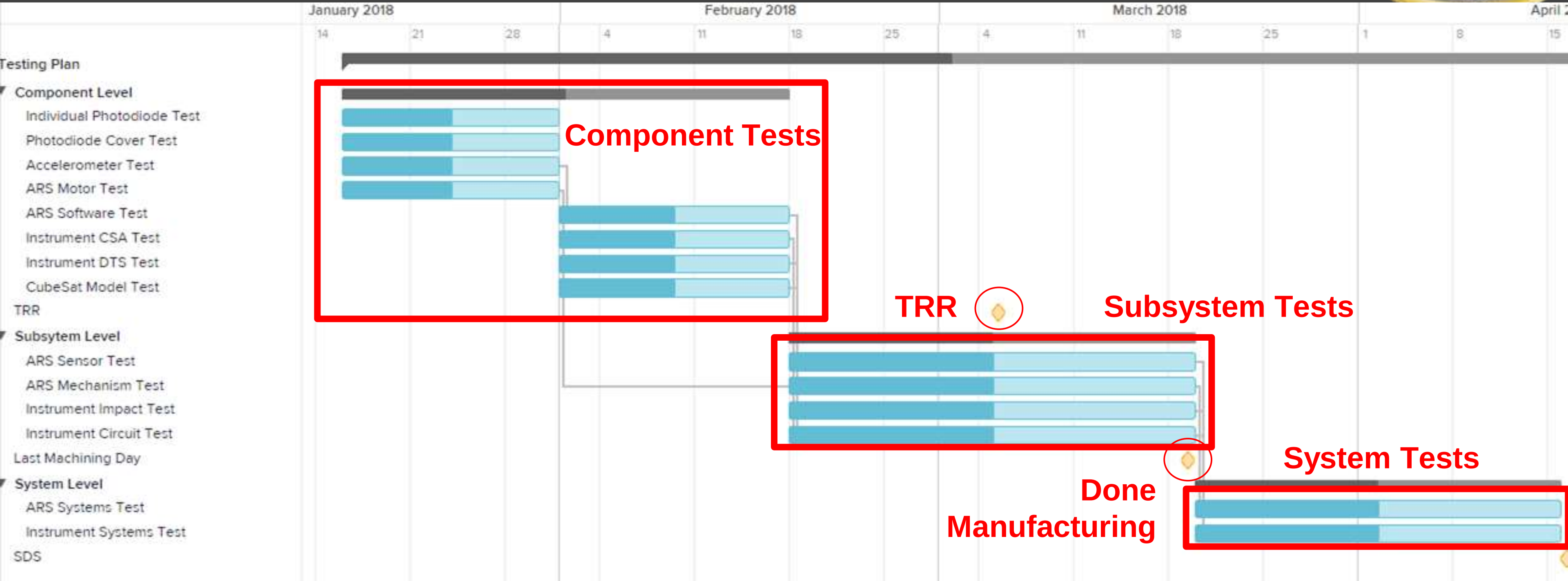
Completed | Future Work

Deliverables	Management	Safety/Test	Instrument	Structure	Mechanisms	Sensors
PDD	Gantt Chart	Research	Material selection	Subsystem layout	Tilt locking design	Full sky coverage
CDD	Budget	Requirements	CAD model	Refined layout	Material selection	Accuracy
PDR	Org Chart	Facilities	RT trigger design	Avionics model	CAD models	Circuit design
CDR	WBS	Procedures	Post processing design	Mass budget	Procurement	Algorithm
FFR	Cost Plan	Equipment	Instrument PCBs	Simulations	Manufacturing	Software
MSR	Test Plan	Assembly	Instrument shell	Procurement	Assembly	PCB
TRR	Risk Matrix	Transportation	Microcontroller & embedded software	Manufacturing	Integration	Calibration
AIAA	ICD documents	Staffing	Lab test	Assembly	Environment test	Mounting
SPR			Impact test	Verification	Validation	Integration
SPP			Validation	Integration		Environment Test
PFR				Validation		Validation

Work Plan


December 2017
January 2018
February 2018
Spring Semester
START
3D Print Photodiode Cover
Manufacture Door
Individual Photodiode Test
Photodiode Cover Test
Accelerometer Test
Manufacture Tilting Mechanism
ARS Motor Test
Identify and Quantify Manufacturing/Moun...
Finalize Post Processing Algorithms
Finalize Sun Sensing Algorithms
MSR Work
MSR
Rework Model's
Microcontroller PCB
CSA PCB
ARS PCB
Photodiode PCB
Convert Sun Sensing to Arduino sketch
ARS Software Test
Instrument CSA Test
CubeSat Model Test
Instrument DTS Test
ARS and Structure Integration
Test Sun Sensing Algorithms
Manufacture Instrument
Manufacture CS Structure
Component Level Testing
Embed Trigger software
Integrate Sun Sensing, Accelerometer, an...
Critical Path
Component Manufacturing
**PCB Manufacturing
Subsystem Assembly
System Assembly

Testing Plan



Thank you!

Feedback?

Slide Directory

Backup Slides

Functional Requirement Validation

	Desired Outcome	Test
FR 1	Instrument secured in CubeSat, 2U and 6U measurements not exceeded	Fit-check and inspection
FR 2	Instrument detects dust particles	IMPACT vacuum chamber test
FR 3	Shaded door is opened	Sun determination test
FR 4	Shaded side is tilted to 45°	Tilting test
FR 5	Electronics command ARS tilt and doors, collect signals from instrument	Tilting test, IMPACT vacuum chamber test
FR 6	Event detection and ARS closed loop control	IMPACT vacuum chamber test, ARS system test

Cleaning

- All instrument machined components must be cleaned and put through an acetone and ethanol ultrasonic bath
- PCB is cleaned with ethanol
- Design cannot have trapped volumes or outgassing materials

Ultrasonic bath at BioServe

Interior of bath

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

Changes since PDR

Change	Reasoning
Added cleaning requirements	Customer requested component cleaning in preparation for vacuum testing
Changed impact testing scope	Focusing on wire electrode breaking, not tension (wire splits into 2+ separate pieces)
Changed tilting mechanism	Switched to stepper motor with lead screw from servo motor
Added 13th photodiode	Increase full sky coverage and accuracy

Risk Evaluation

Risk Evaluation Criteria - Likelihood

Rating	Qualitative	Quantitative
1	Rare	0-5%
2	Unlikely	5-35%
3	Possible	35-70%
4	Likely	70-95%
5	Certain	95-100%

Risk Evaluation Criteria - Severity

Rating	Qualitative	Schedule/Cost	Technical
1	Insignificant	No reduction in margin	All requirements still met
2	Minor	Small margin reduction	Failed 1 subsystem requirement
3	Moderate	Significant reduction	Failed 2 subsystem requirements or 1 functional requirement
4	Major	All margin consumed	Failed 3 subsystem requirements or 2 functional requirements
5	Catastrophic	Schedule/cost overrun	Failed 4 subsystem requirements or 3 functional requirements

Structures Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5					
	4			STRUCT-2		
	3	STRUCT-5	STRUCT-6			
	2		STRUCT-7		STRUCT-1	
	1		STRUCT-4	STRUCT-3		

Legend							
(green)	Low (1-3)	(yellow)	Moderate (4-9)	(orange)	High (10-15)	(red)	Extreme (16-25)

Structures Risk Descriptions

Risk	Description	Likelihood	Severity	Total
STRUCT-1	Misalignment in CubeSat build	2	4	8
STRUCT-2	Wire electrodes break or detach	4	3	12
STRUCT-3	Additions to instrument cause it to not fit	1	3	3
STRUCT-4	DTS or field plates not isolated	1	2	2
STRUCT-5	Electrode length decreases FOV	3	1	3
STRUCT-6	Magnet array mounting errors	3	2	6
STRUCT-7	Other part of impact test apparatus fails	2	2	4

Instrument Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5				INST-2	
	4					
	3			INST-1		
	2		INST-3			
	1			INST-4		

Legend			
Low (1-3)	Moderate (4-9)	High (10-15)	Extreme (16-25)

Instrument Risk Descriptions

Risk	Description	Likelihood	Severity	Total
INST-1	Magnetic shielding doesn't keep electrons out	3	3	9
INST-2	Difficulty acquiring past data for test	5	4	20
INST-3	Plastics outgass in vacuum	2	2	4
INST-4	Plastics provide insufficient insulation	1	3	3

ARS Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5	ARS-2				
	4				ARS-1,6	
	3	ARS-5				
	2				ARS-4	
	1			ARS-7		ARS-3

Legend							
(green)	Low (1-3)	(yellow)	Moderate (4-9)	(orange)	High (10-15)	(red)	Extreme (16-25)

ARS Risk Descriptions

Risk	Description	Likelihood	Severity	Total
ARS-1	Photodiode noise	4	4	16
ARS-2	Photodiode mounting inaccurate	5	1	5
ARS-3	Power/data allocations	1	5	5
ARS-4	Photodiodes too unique to correlate	2	4	8
ARS-5	Poor diode performance in low light	3	1	3
ARS-6	Inconsistency in apertures	4	4	16
ARS-7	Reflected light impacts measurements	1	3	3

Mechanisms Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5					
	4	MECH-7			MECH-1	
	3					
	2				MECH-2, 3	
	1				MECH-5, 6	MECH-4

Legend			
Low (1-3)	Moderate (4-9)	High (10-15)	Extreme (16-25)

Mechanisms Risk Descriptions

Risk	Description	Likelihood	Severity	Total
MECH-1	Mechanisms mounting errors	4	4	16
MECH-2	Door motor can't open door (torque lock)	2	4	8
MECH-3	Leg joints lock	2	4	8
MECH-4	Legs bend or break	1	5	5
MECH-5	Mechanisms take up too much room	1	4	4
MECH-6	False door button trigger	1	4	4
MECH-7	Motors drift when locked	4	1	4

Electronics Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5					
	4				ELEC-1	
	3					ELEC-4
	2				ELEC-2	
	1	ELEC-5				ELEC-3

Legend							
(green)	Low (1-3)	(yellow)	Moderate (4-9)	(orange)	High (10-15)	(red)	Extreme (16-25)

Electronics Risk Descriptions

Risk	Description	Likelihood	Severity	Total
ELEC-1	Need to remake PCB	4	4	16
ELEC-2	Break a microcontroller during testing	2	4	8
ELEC-3	Unable to meet real-time requirements	1	5	5
ELEC-4	Noise from connections/EMI	3	5	15
ELEC-5	Customer- designed circuits don't work	1	1	1

Software Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5	SOFT-3, 4				
	4					
	3					SOFT-2
	2				SOFT-5	
	1	SOFT-1				

Legend			
Low (1-3)	Moderate (4-9)	High (10-15)	Extreme (16-25)

Software Risk Descriptions

Risk	Description	Likelihood	Severity	Total
SOFT-1	False triggers	1	1	1
SOFT-2	No triggers (same as ELEC-4)	3	5	15
SOFT-3	Inability to detect in quick succession	5	1	5
SOFT-4	Don't know SNR	5	1	5
SOFT-5	Converting to real time in Ada	2	4	8

Integration Testing Risk Matrix (Backup)

		Severity				
		1	2	3	4	5
Likelihood	5					INT-4
	4					
	3					
	2			INT-1, 2, 5		
	1				INT-3	INT-6

Legend							
	Low (1-3)		Moderate (4-9)		High (10-15)		Extreme (16-25)

Integration Testing Risk Descriptions

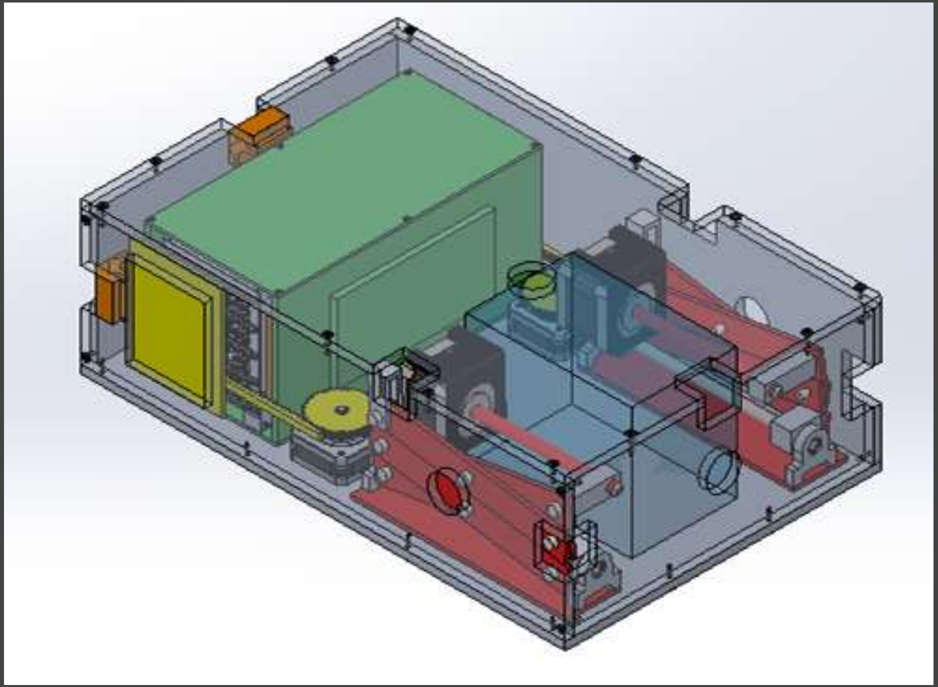
Risk	Description	Likelihood	Severity	Total
INT-1	Instrument is not clean enough	2	3	6
INT-2	Schedule IMPACT lab for testing	2	3	6
INT-3	Can't find ARS testing location	1	4	4
INT-4	Can't test dust detection except in vacuum	5	5	25
INT-5	Schedule impact test in idea forge	2	3	6
INT-6	Use budget on unexpected purchases	1	5	5

Mitigation Impact on Risks

Risk	Description	Likelihood	Severity	Total
INT-4	Can only test dust instrument in vacuum	5	3	15
INST-2	Don't have past test data	5	3	15
ELEC-1	Need to remake PCB	3	2	6
MECH-1	Mechanism mounting errors	2	4	8
ARS-1	Photodiode noise	2	4	8
ARS-6	Inconsistencies in photodiode apertures	4	2	8
ELEC-4	Noise from connections and EMI	2	5	10
STRUCT-2	Wire electrode displacement exceeds limit	3	3	9

Structures

Mass Budget



System	Mass (kg)
Dust Instrument	1.40
Door Mechanism	1.01
Scissor Lift Mechanism	1.24
Photodiodes	0.25
Microcontrollers	0.15
Avionics (Out of Scope)	1.50
CubeSat Structure	4.65
Total	**10.20 kg**

2U Instrument Design

Specific Requirement:

2.1 - The detector portion of the instrument shall fit within a 2U volume, not including the microcontroller.

Why?

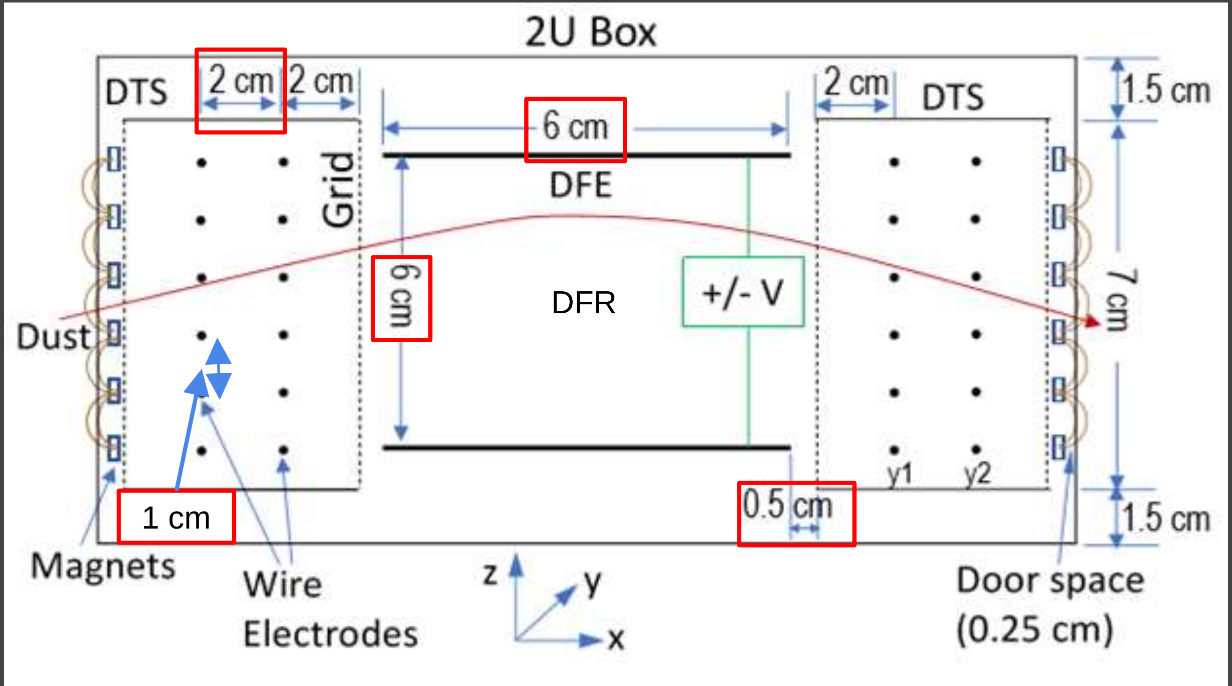
The customer wants a 2U (10 x 20 x 11.35 cm) dust instrument

Designs Driven:

- **Dust trajectory sensor (DTS)**
- Charge sensitive amplifiers board (CSAs)
- Deflection Field Electrode (DFE)
- Magnetic shielding

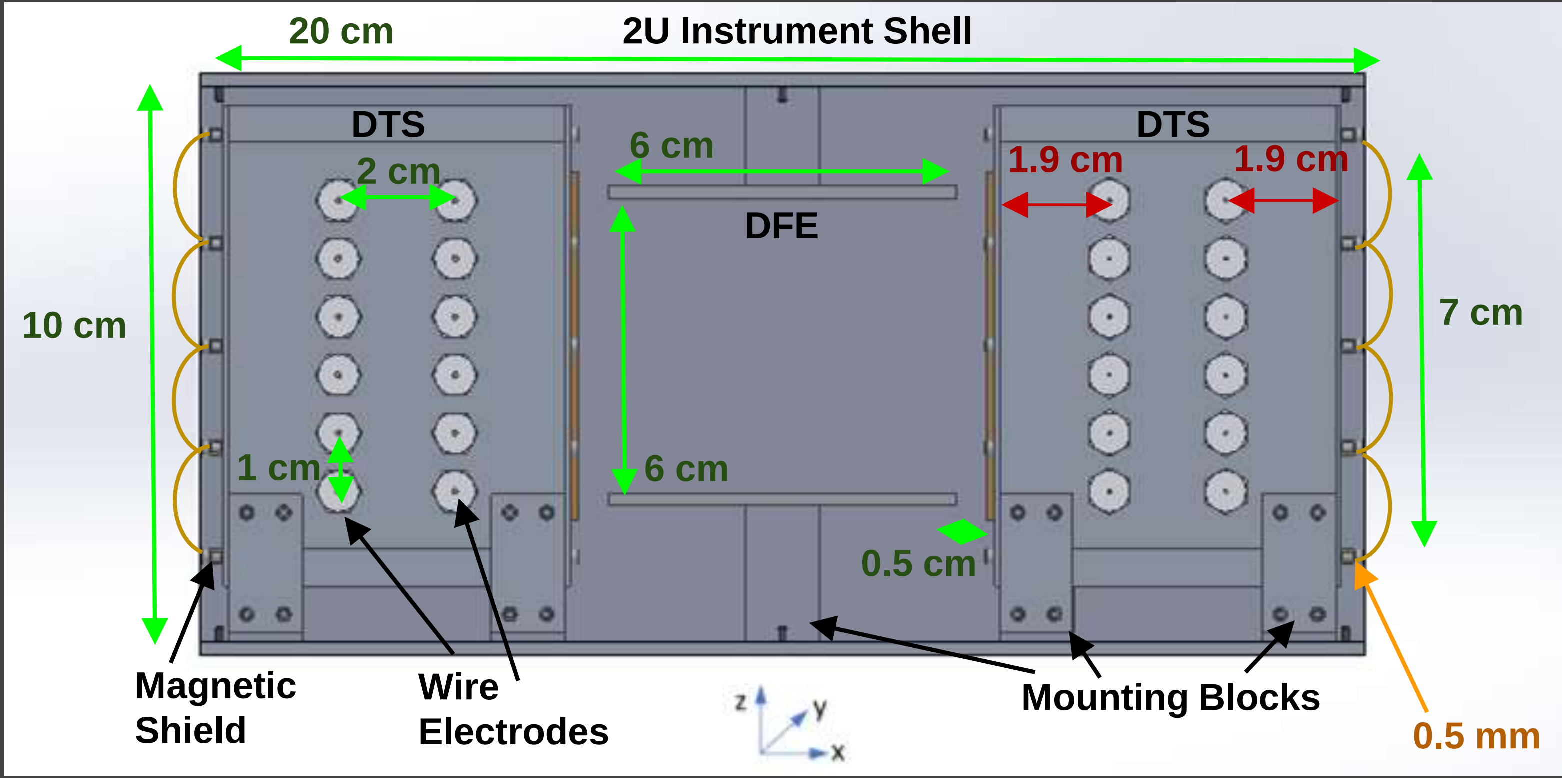
Customer's DTS

2U Instrument Design



Customer's Optimal Dust Measurement 2U Instrument Design

2U Instrument Design



Dust BUSTER's 2U Instrument Design

2U Instrument Design

What was designed:

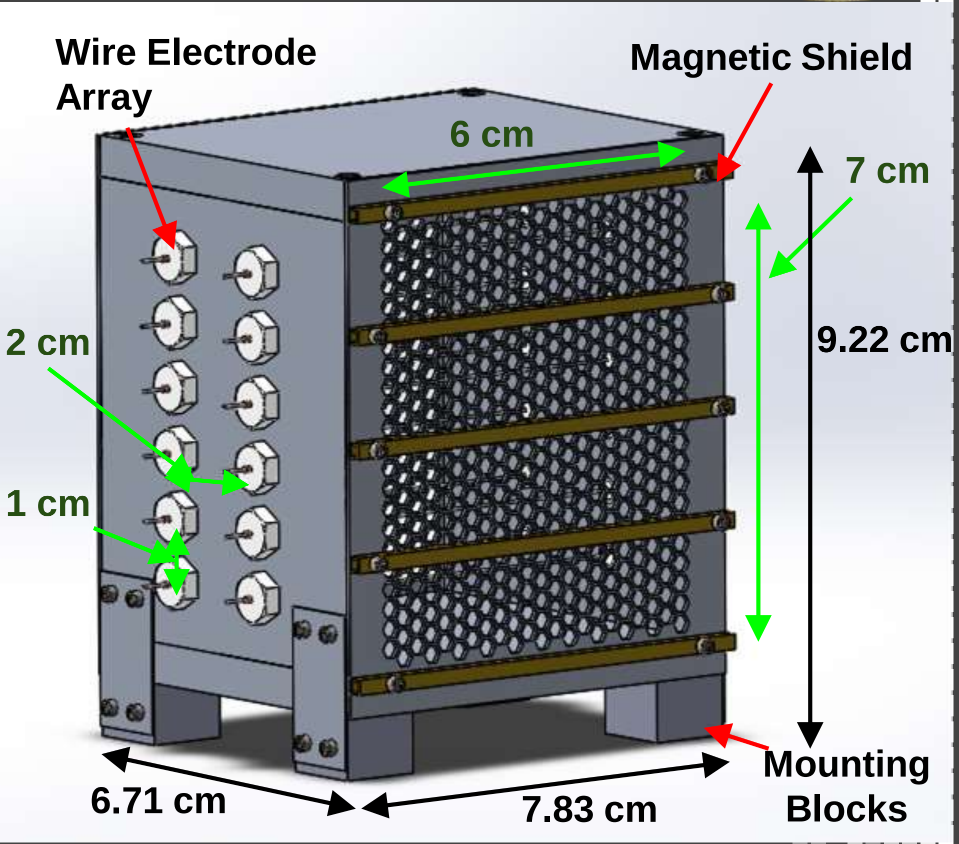
- Wire electrode arrays
- Magnetic electron shield
- Mounting system

Influences/Considerations:

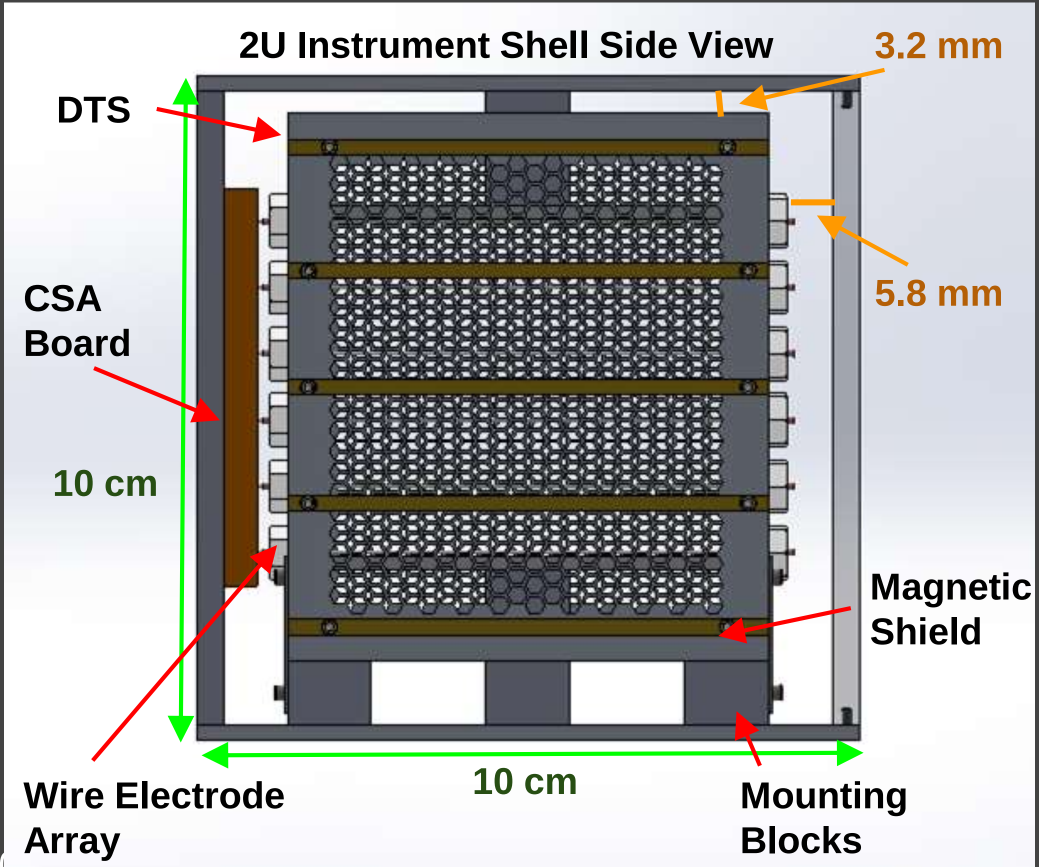
- Aperture of the instrument
- Customer schematic

Dependencies:

- CSA board height and location
- Instrument shell wall thickness



2U Instrument Design



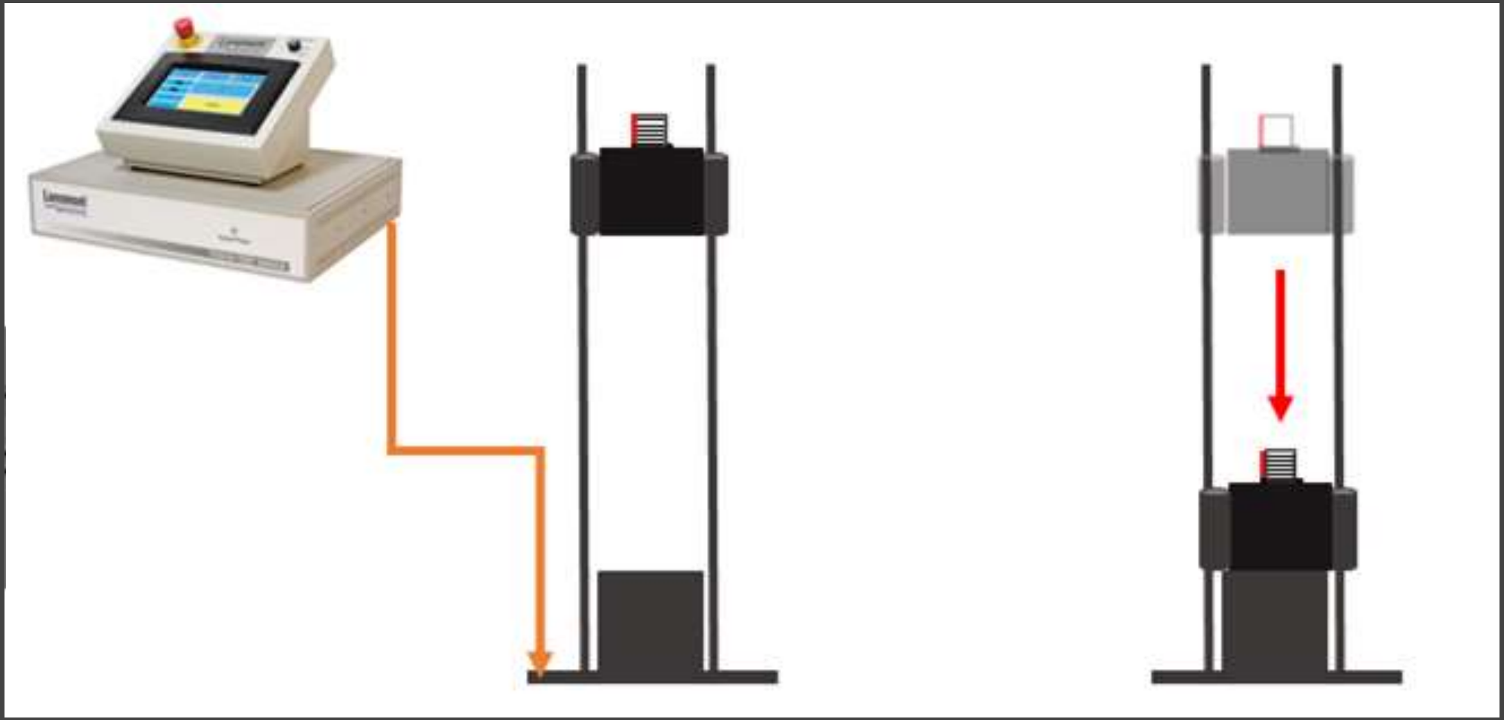
All instrument components contained within 2U volume

Requirement 2.1 satisfied

Verifying Wire Electrode Design

- Our model shows that the wire electrode system should not break after a 10 m/s perfectly inelastic collision
- Testing model with Lansmont 15D Shock Test Machine
  - Located in the Idea Forge with walk-in availability
- Testing for failure of wire electrodes
  - See which impact velocity causes the electrodes to break (become two separate pieces or detached)
  - Wire Electrode strength may not be determined if the DTS breaks in some other manner
- Testing with a constructed Dust Trajectory Sensor

Lansmont 15D Impact Testing



Impact Collision Calculations

Assumptions:

- Perfectly inelastic collision (v_f = 0 m/s)
- Point mass model for CubeSat

Knowns:

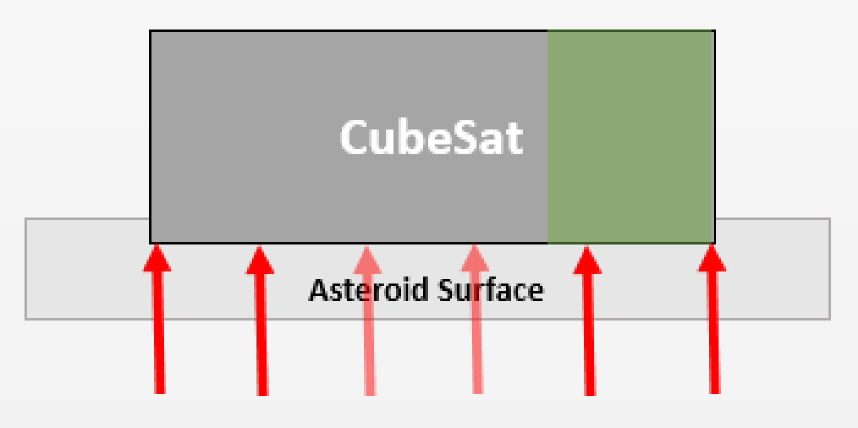
- CubeSat mass (m_{CS}) = 12 kg (max)
- Impact velocity (v_i) = 10 m/s

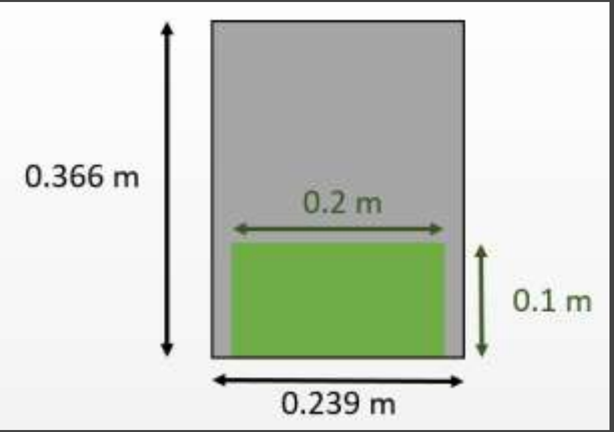
$$J_{CS} = m_{CS}(v_f - v_i)_{CS} = 12(10 - 0) = 120Ns$$

$$J_{CS} = F_{impact}\Delta t \Rightarrow F_{impact} = J_{CS}\Delta t$$

Impact Collision Calculations

Point mass force will likely be distributed

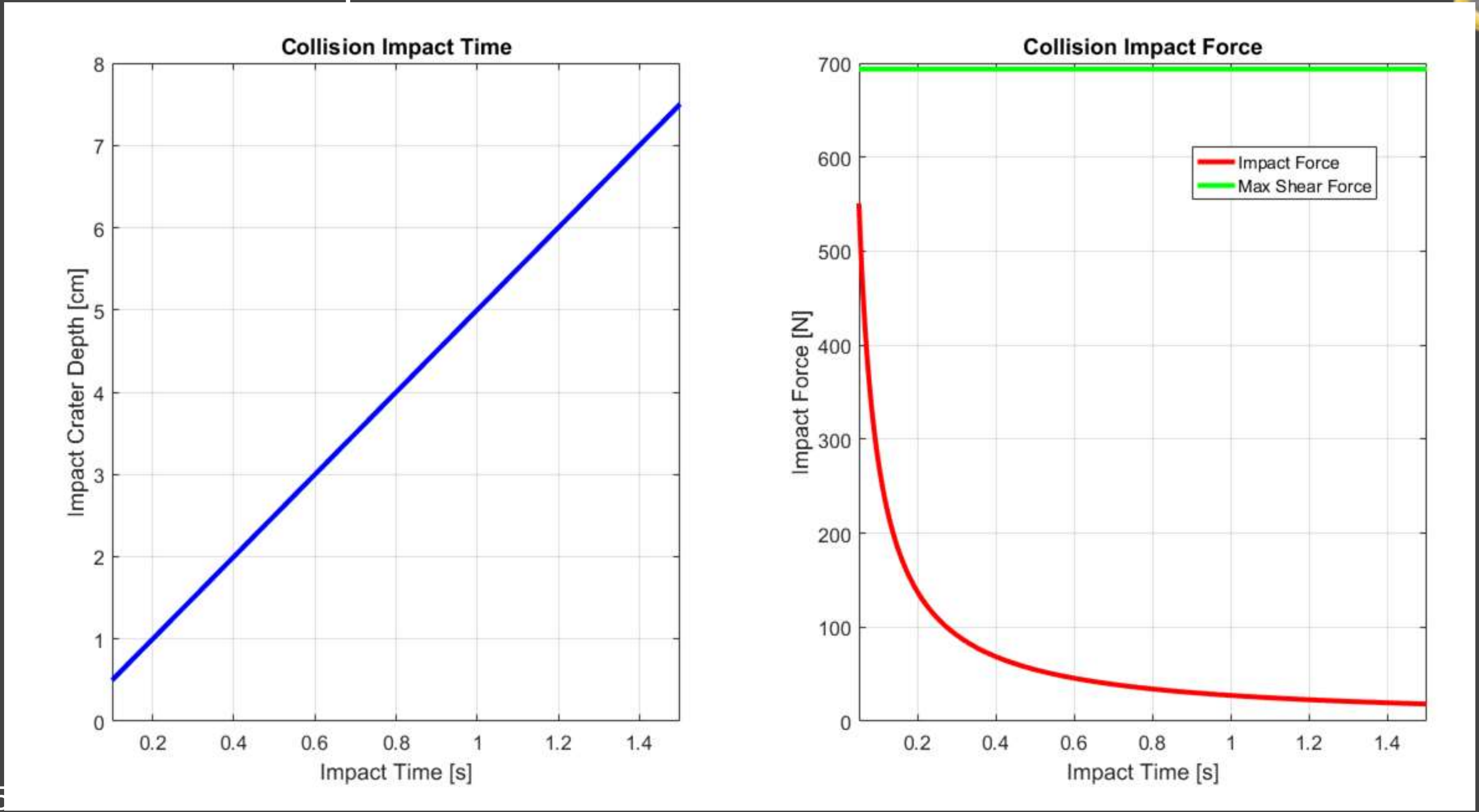




$$P_{impact} = \frac{F_{impact}}{SA_{base}} \Rightarrow \frac{F_{impact,DI}}{SA_{base,DI}} = \frac{F_{impact,CS}}{SA_{base,CS}}$$

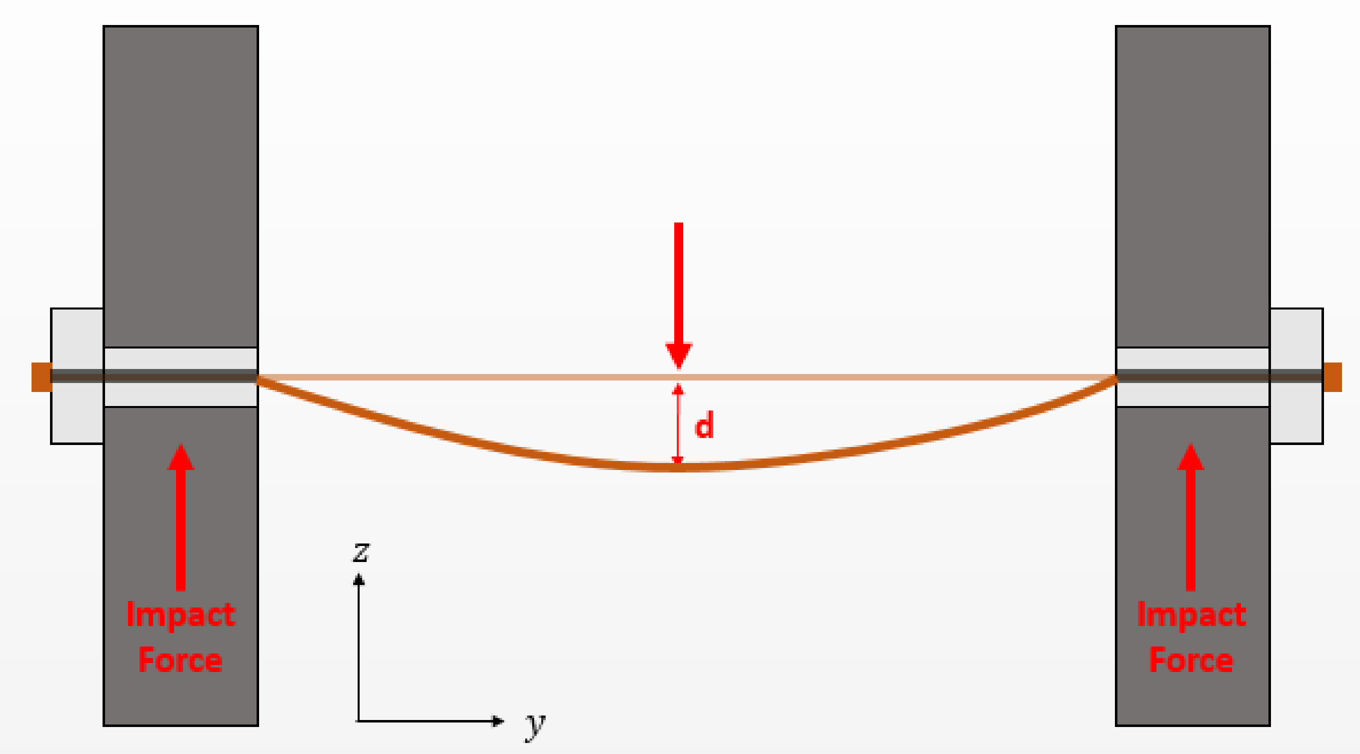
$$\Rightarrow F_{impact,DI} = F_{impact,CS} \times \frac{SA_{base,DI}}{SA_{base,CS}} = 0.2286 F_{impact,CS}$$

Impact Collision Calculations

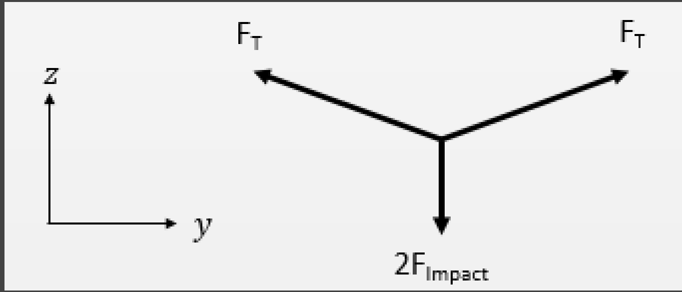


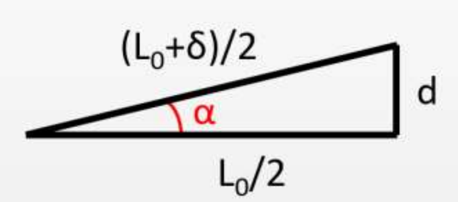
Wire Electrode Impact Analysis

Modeling worse case scenario.



Wire Electrode Impact Analysis





Given:

- Yield Strength (τ): 199.9 N/mm^2
- Wire Length (L_0): 7.0 mm
- Modulus of Elasticity (E): 117.0 N/mm^2

Assumptions: Rigid Body Analysis

Find: elongation (δ), deflection distance (d), deflection angle (α), and impact force that would break the wire (F_{impact})

$$\delta = L_0 \times \frac{\tau}{E} = 0.042mm$$

$$\alpha = \sin^{-1}\left(\frac{d}{\frac{L_0+\delta}{2}}\right) = 1.982^o$$

$$d = \sqrt{\left(\frac{L_0+\delta}{2}\right)^2 + \left(\frac{L_0}{2}\right)^2} = 1.211mm$$

$$F_{impact} = F_T \sin(\alpha) = \boxed{0.4752N}$$

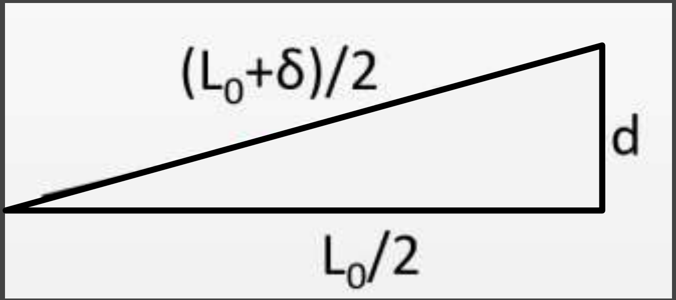
Surviving Impact - Model

Given:

- Yield Strength (τ): 215 N/mm^2
- Wire Length (L_0): 6.0 mm
- Modulus of Elasticity (E): 200 N/mm^2

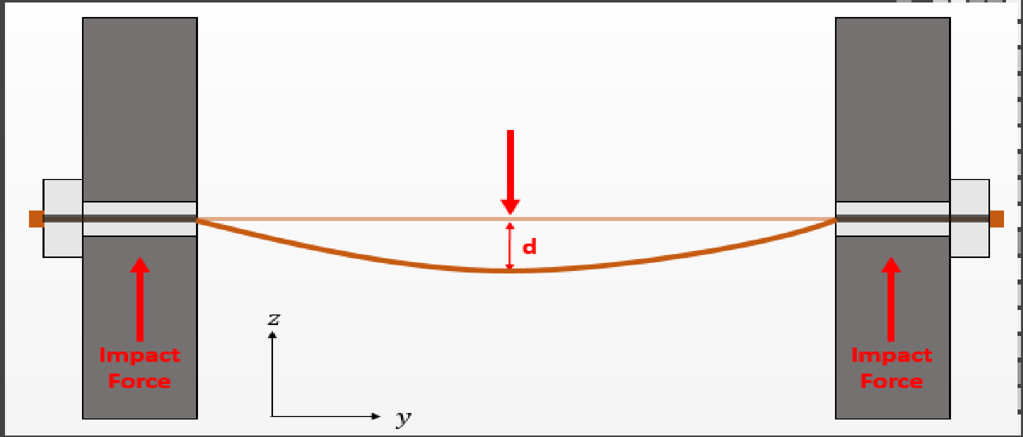
Assumptions: Rigid Body Analysis

Find: elongation (δ), deflection distance (d)

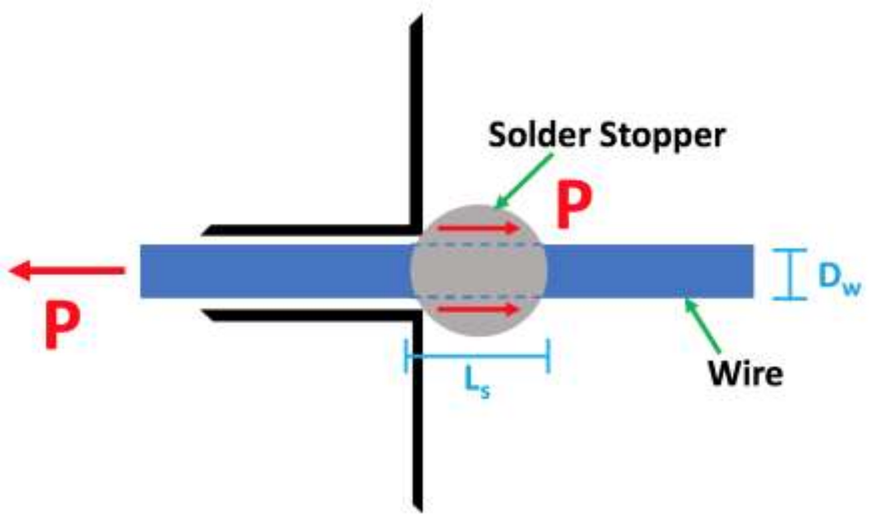


$$\delta = L_0 \times \frac{\tau}{E} = 0.0645mm$$

$$d = \sqrt{\left(\frac{L_0+\delta}{2}\right)^2 + \left(\frac{L_0}{2}\right)^2} = 1.391mm$$



Surviving Impact - Solder Stopper Analysis



$$\tau = \frac{P}{A_{contact}}$$

$$\tau = \frac{P}{\pi L_s D_w} \qquad \sigma_n = \frac{4P}{\pi (D_w)^2}$$

$$\left(\frac{4L_s}{D_w}\right)\tau = \sigma_n$$

Given:

$$\left.\begin{aligned} \tau_{max} &\approx 30 \text{ MPa} \\ D_w &= 0.5 \text{ mm} \\ L_s &> 2.1 \text{ mm} \end{aligned}\right\} \sigma_n > 504 \text{ MPa}$$

Same as ultimate strength of wire

ARS Sensors

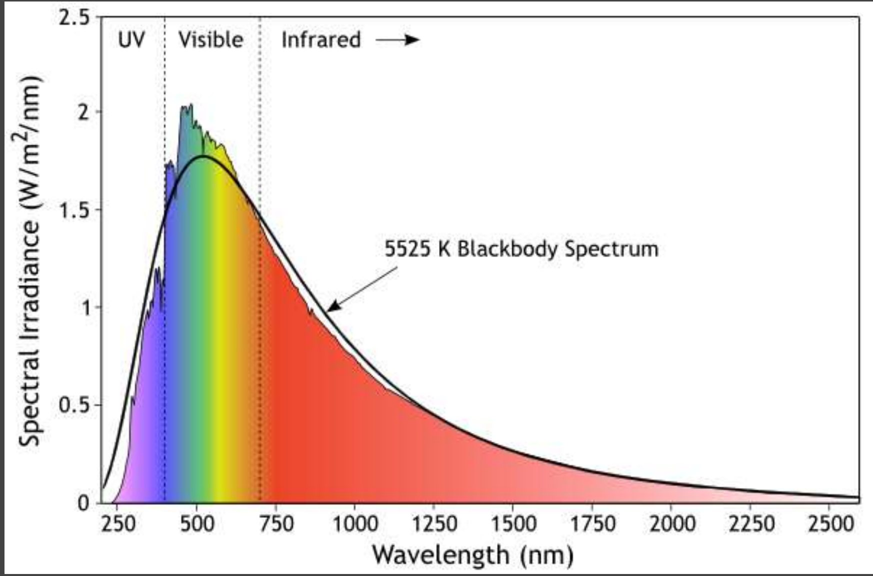
ARS Component Level Tests

- Sensor Tests
  - Testing and calibration:
    - Individual photodiode outputs.
    - Individual photodiodes and covers for manufacturing tolerances.
    - Photodiode housing mounting on CubeSat structure.
    - Accelerometer mounting
- Mechanisms Tests
  - Testing
    - Individual parts for errors in manufacturing
    - Test tilting matches model (independent of other systems)
- Software Tests
  - Module level testing of algorithms

Sun Knowledge - Accuracy

Need to know the current output of the photodiodes

- Solar irradiance spectrum is well known and provides power at every wavelength
- Photodiode relative spectral sensitivity gives relative power absorbed at every wavelength



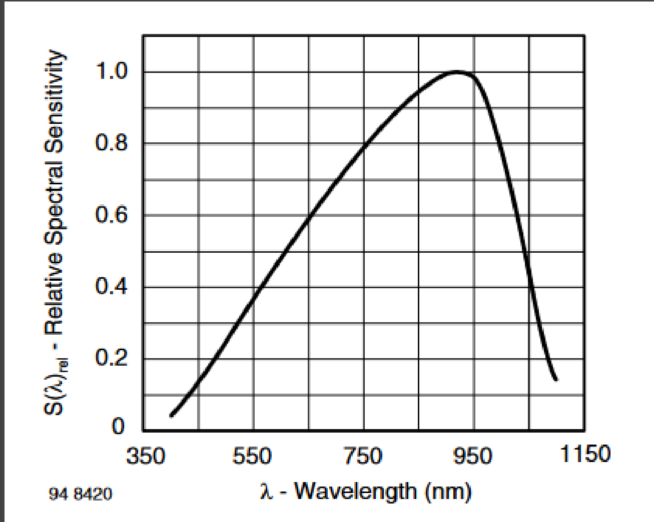
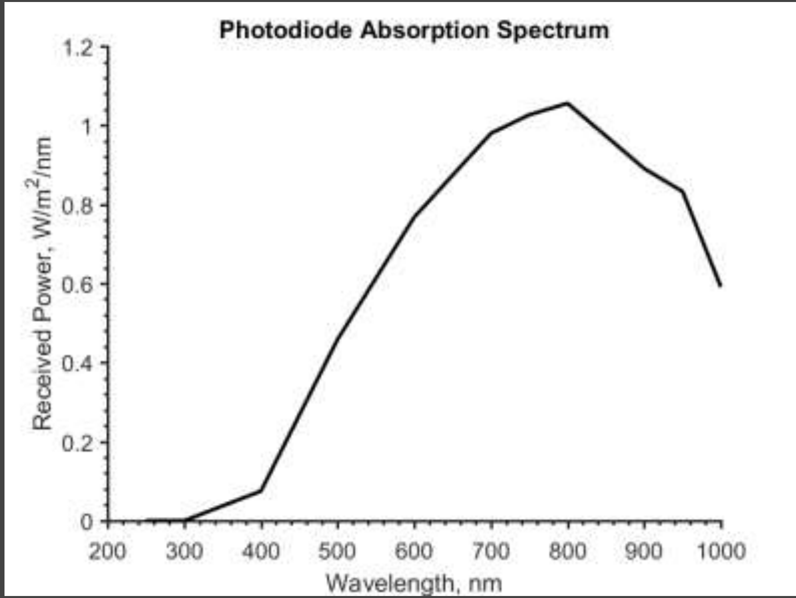


Fig. 6 - Relative Spectral Sensitivity vs. Wavelength

Sun Knowledge – Accuracy



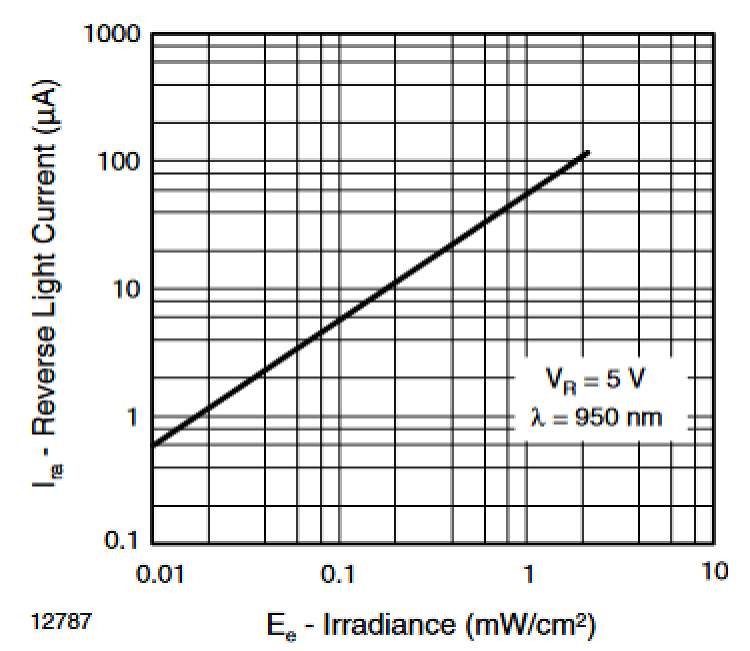
Multiply solar irradiance spectrum and photodiode relative spectral sensitivity at each wavelength
Result is photodiode power per area across the full spectrum

Integrate the photodiode absorption spectrum to get the total power the photodiode will receive.
Ir = 457.5 W/m^2
P = IA = **3.4 mW**

Sun Knowledge - Accuracy

Expected Irradiance on photodiodes:
Ee = 0.4575 mW/cm^2
From gain curve on datasheet
I = 30 µA

Microcontrollers measure voltage, not current
Voltage measured across a resistor to ground would be too small for Teensy microcontroller, so **voltage needs to be amplified**

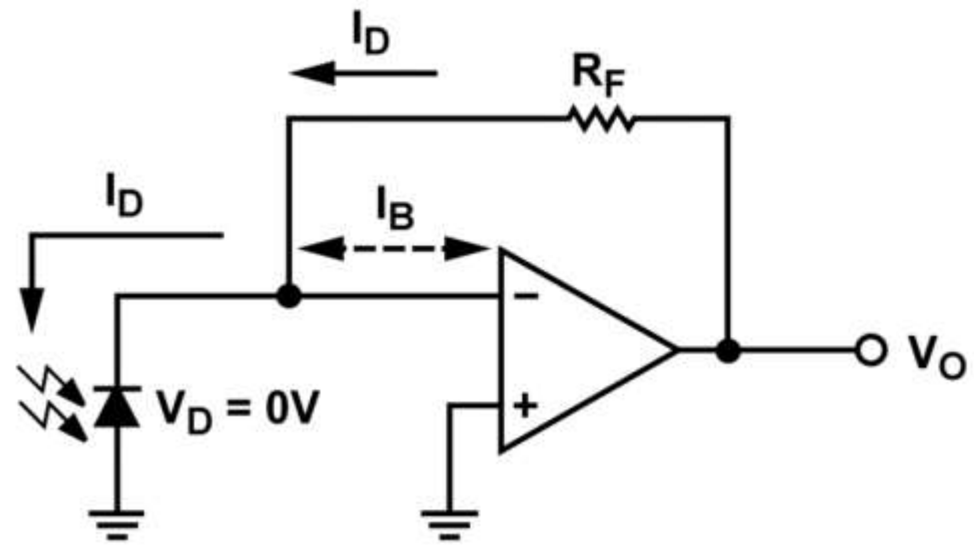


Sun Knowledge – Accuracy

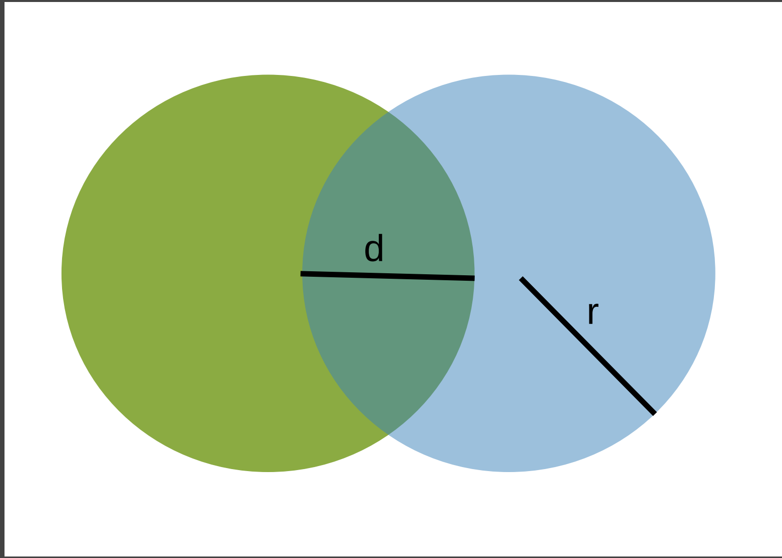
Implement a transimpedance amplifier to boost the signal and convert current to voltage.

Vo = Id*Rf
Maximum current of 30 μA
Rf of 200 kΩ
Vo max = 4.8 V

Output voltage is **within microcontroller range**



Photodiode Covers – Exposed Area



$$A = 2R^2 \cos^{-1}\left(\frac{d}{2R}\right) - \frac{1}{2} d \sqrt{4R^2 - d^2}$$

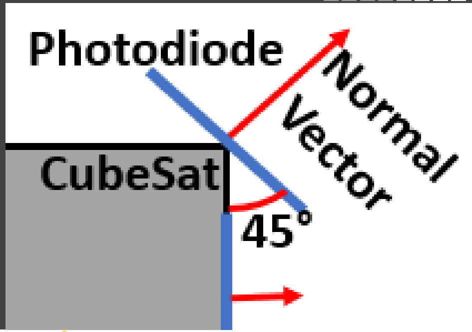
Sun Sensor Design

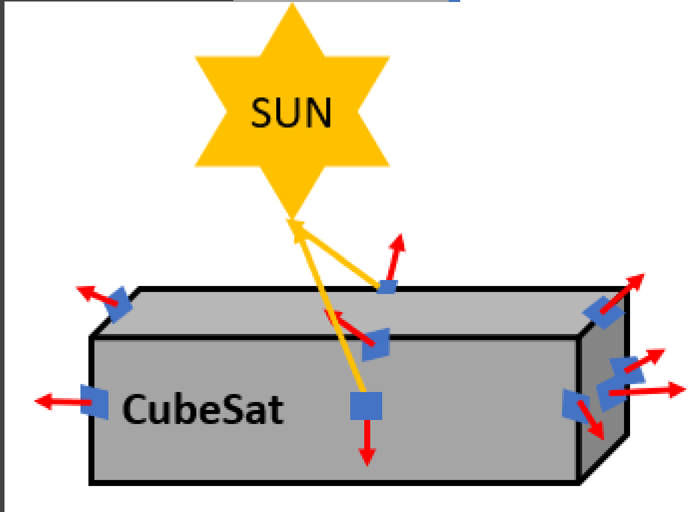
Why do we need the Sun position?

- Need to know which side of the CubeSat to actuate
  - Solar wind from the Sun can create erroneous data
- Solar keep-out and 45° actuation not always possible
  - Actuate to within 1 of highest possible angle

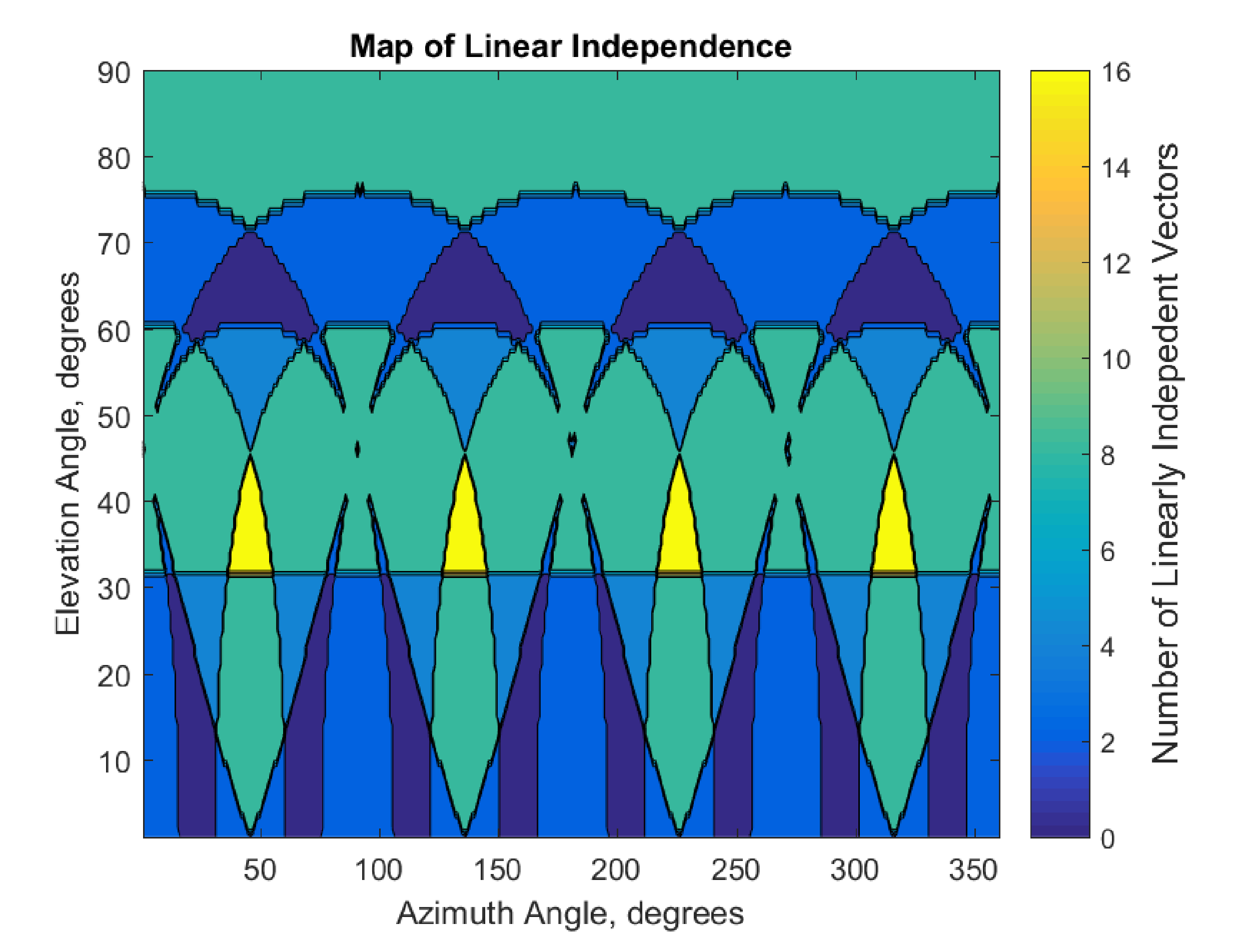
How? - Photodiodes

- Edges and side faces will have a sensor
  - Edges mounted 45° off sides, faces flat



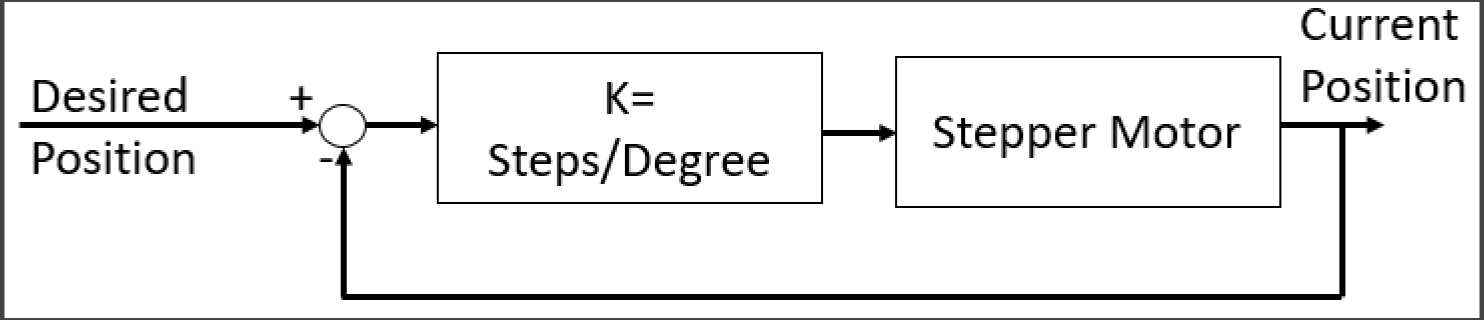


Linear Independence Sky Map



ARS Software: Control Loop Design

- Why?
  - Stepper Motors aren’t perfect, they can skip a step
- How?
  - Use a closed loop control system for the stepper motors
  - Due to discrete steps of stepper motor, only proportional control needed
  - No rise time or overshoot requirements



ARS Software

Why?

- Need to be able to determine optimal angle for Cubesat to tilt and send motor commands for actuation

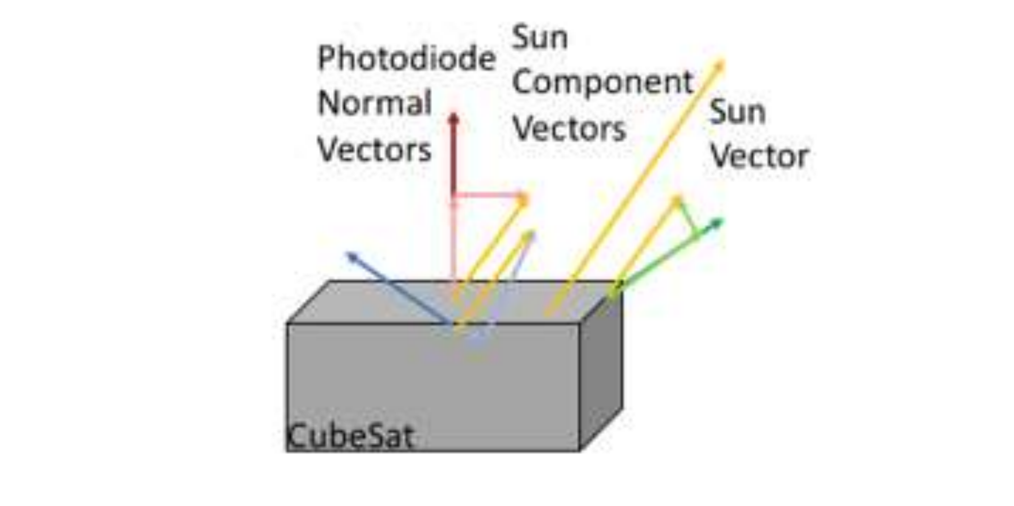
How? Sample 13 photodiodes for sun position and sample accelerometer for closed loop control

- Read in analog values from photodiodes and convert to digital
- Convert digital photodiode values to relative sun vector angles
- Determine 3D sun vector
- Determine correct angle to tilt and which side
- Ensure tilting is correct with accelerometer feedback
- Send correct voltage and step amounts to motors

Determining the Sun Vector

- The Sun
  - 1 vector

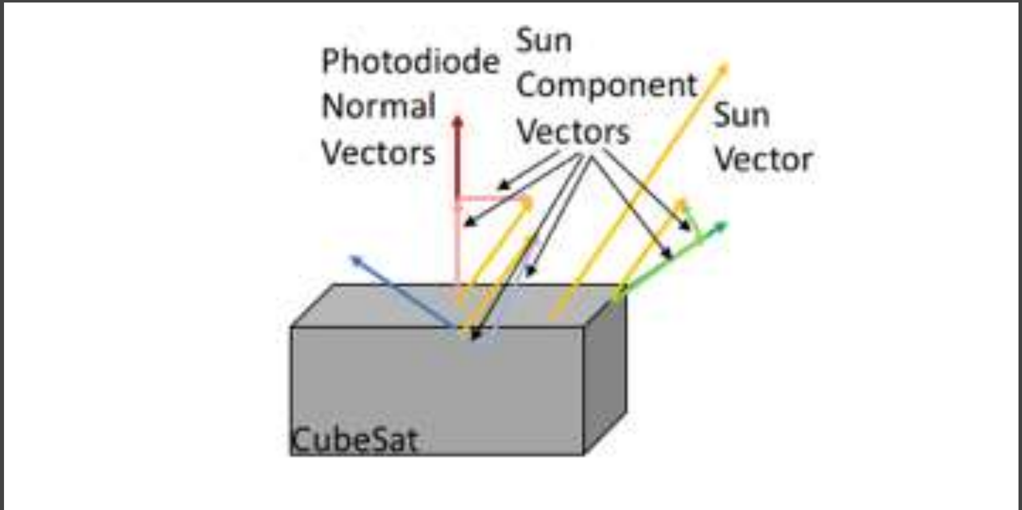
- From 3 diodes
  - 3 vectors
  - 3 angles



Determining the Sun Vector

- The Sun
  - 1 vector

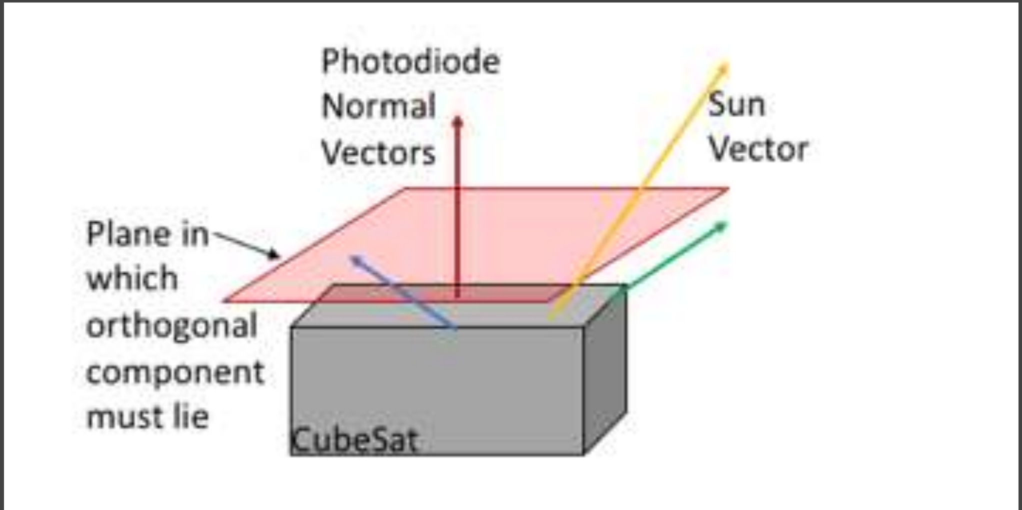
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector Components



Determining the Sun Vector

- The Sun
  - 1 vector

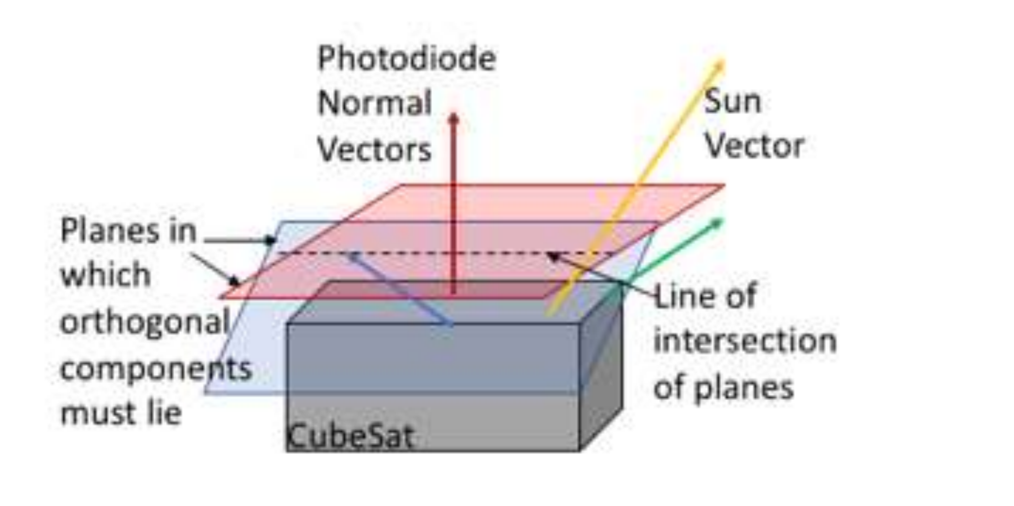
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector components
  - Define 1 plane



Determining the Sun Vector

- The Sun
  - 1 vector

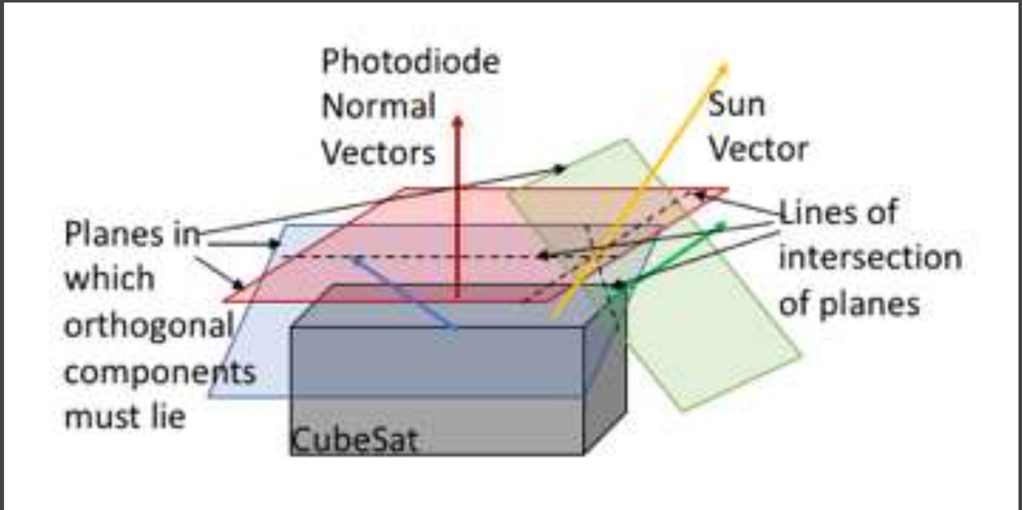
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector components
  - Define 2 planes



Determining the Sun Vector

- The Sun
  - 1 vector

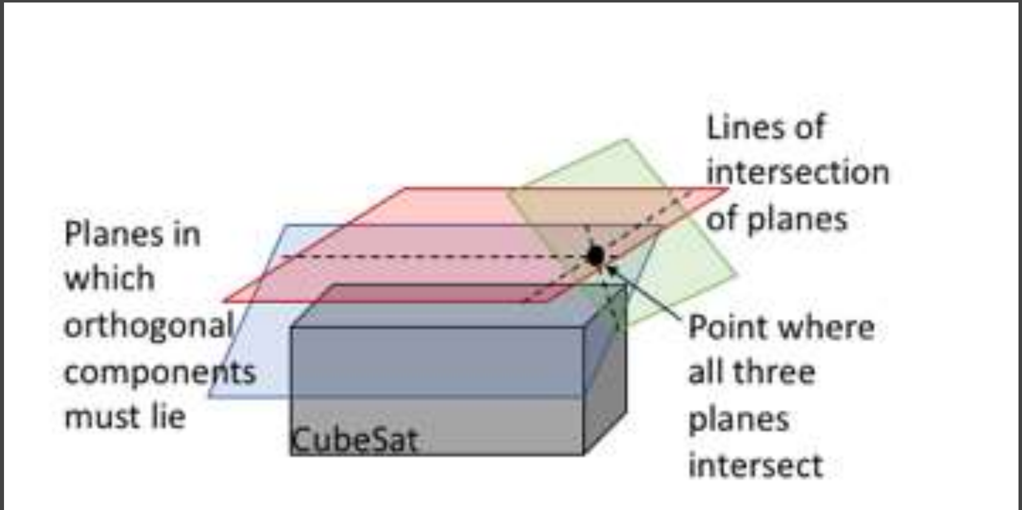
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector components
  - Define 3 planes



Determining the Sun Vector

- The Sun
  - 1 vector

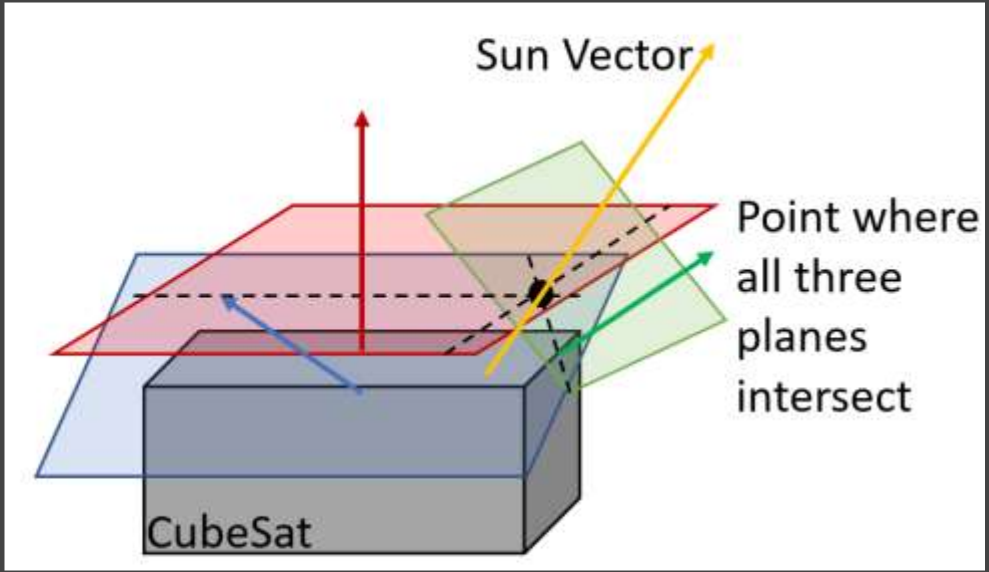
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector components
  - Define 3 planes
  - Intersection point



Determining the Sun Vector

- The Sun
  - 1 vector

- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 planes
  - Intersection point

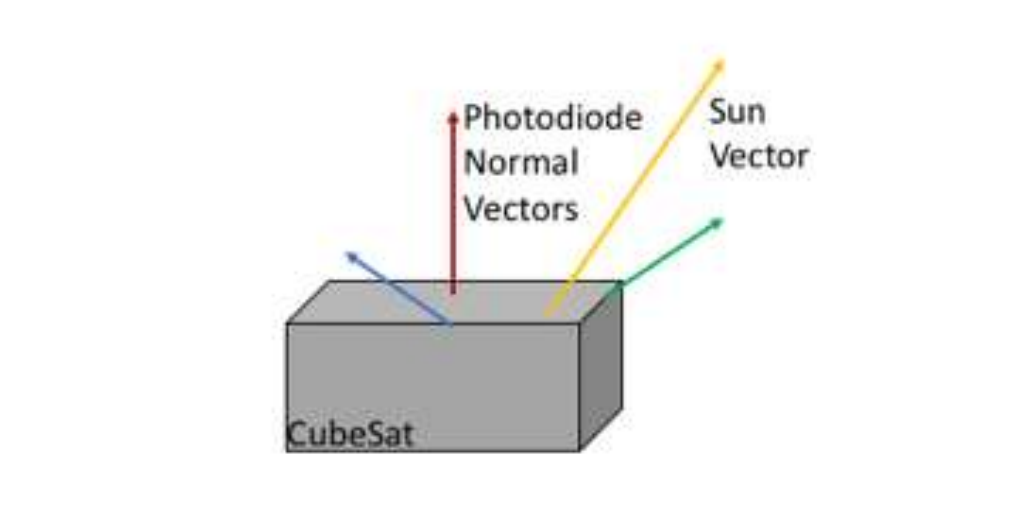


→ Sun Vector

Determining the Sun Vector

- The Sun
  - 1 vector

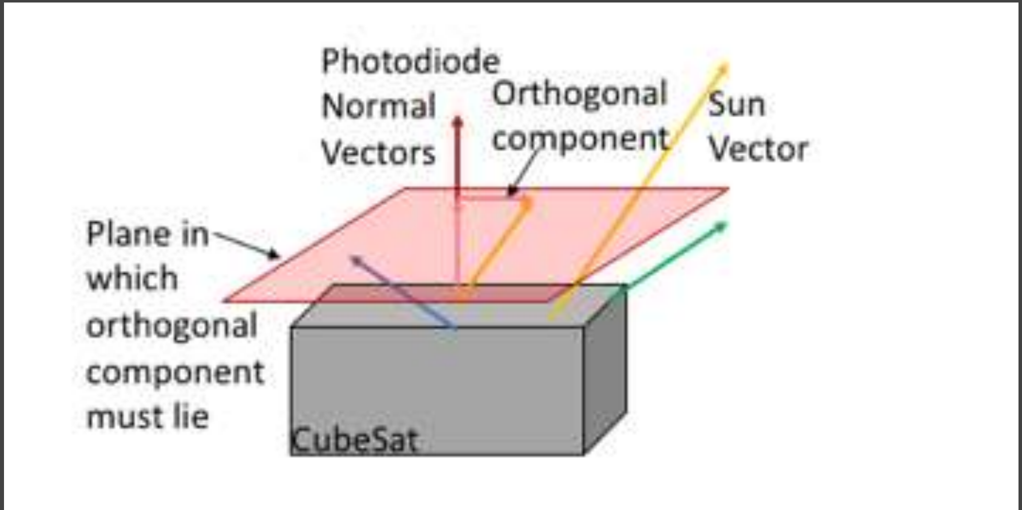
- From 3 diodes
  - 3 vectors



Determining the Sun Vector

- The Sun
  - 1 vector

- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 planes



Equations for Intersection

$$\hat{Z}_{11}\left(X-\hat{Z}_{11}\cos(\alpha_1)\right)+\hat{Z}_{12}\left(Y-\hat{Z}_{12}\cos(\alpha_1)\right)+\hat{Z}_{13}\left(Z-\hat{Z}_{13}\cos(\alpha_1)\right)=0$$

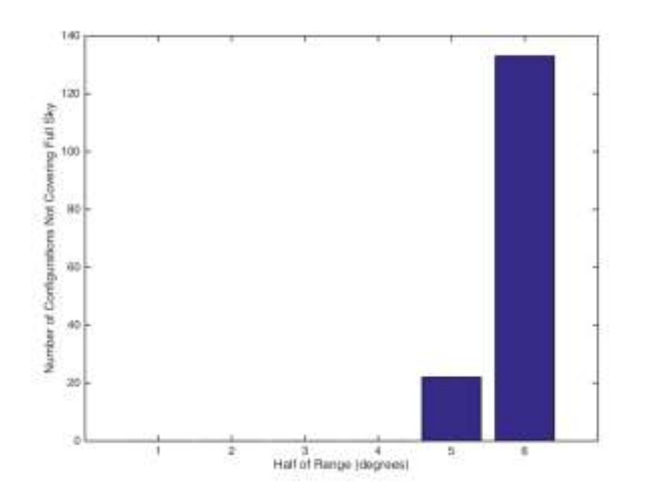
$$\hat{Z}_{21}\left(X-\hat{Z}_{11}\cos(\alpha_2)\right)+\hat{Z}_{22}\left(Y-\hat{Z}_{22}\cos(\alpha_2)\right)+\hat{Z}_{23}\left(Z-\hat{Z}_{23}\cos(\alpha_2)\right)=0$$

$$\hat{Z}_{31}\left(X-\hat{Z}_{31}\cos(\alpha_3)\right)+\hat{Z}_{32}\left(Y-\hat{Z}_{32}\cos(\alpha_3)\right)+\hat{Z}_{33}\left(Z-\hat{Z}_{33}\cos(\alpha_3)\right)=0$$

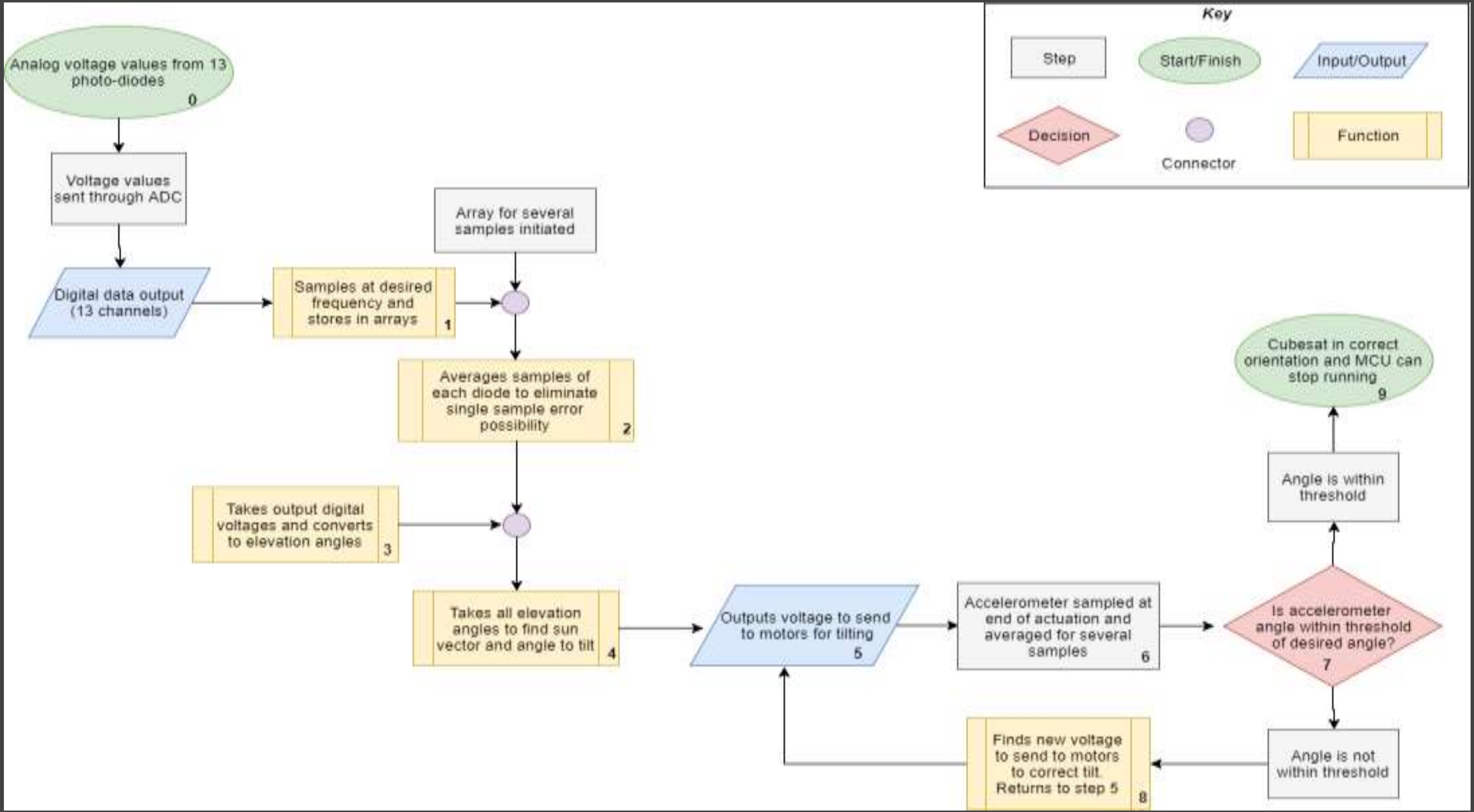
$\hat{Z}_{xy}$ is the xth photodiode vector yth component
α_x is the xth photodiode sun angle
X,Y,Z are the body components of the sun vector

ARS Photodiode Mounting

- Photodiodes will not be placed with perfect angular position
- Need to maintain full sky coverage
  - Based on a Monte-Carlo analysis, we can maintain full sky coverage with 5 of mounting accuracy



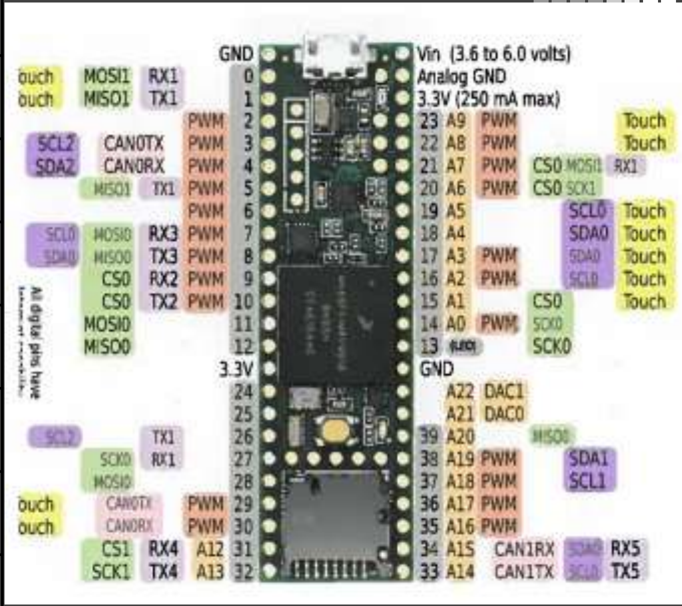
ARS Software



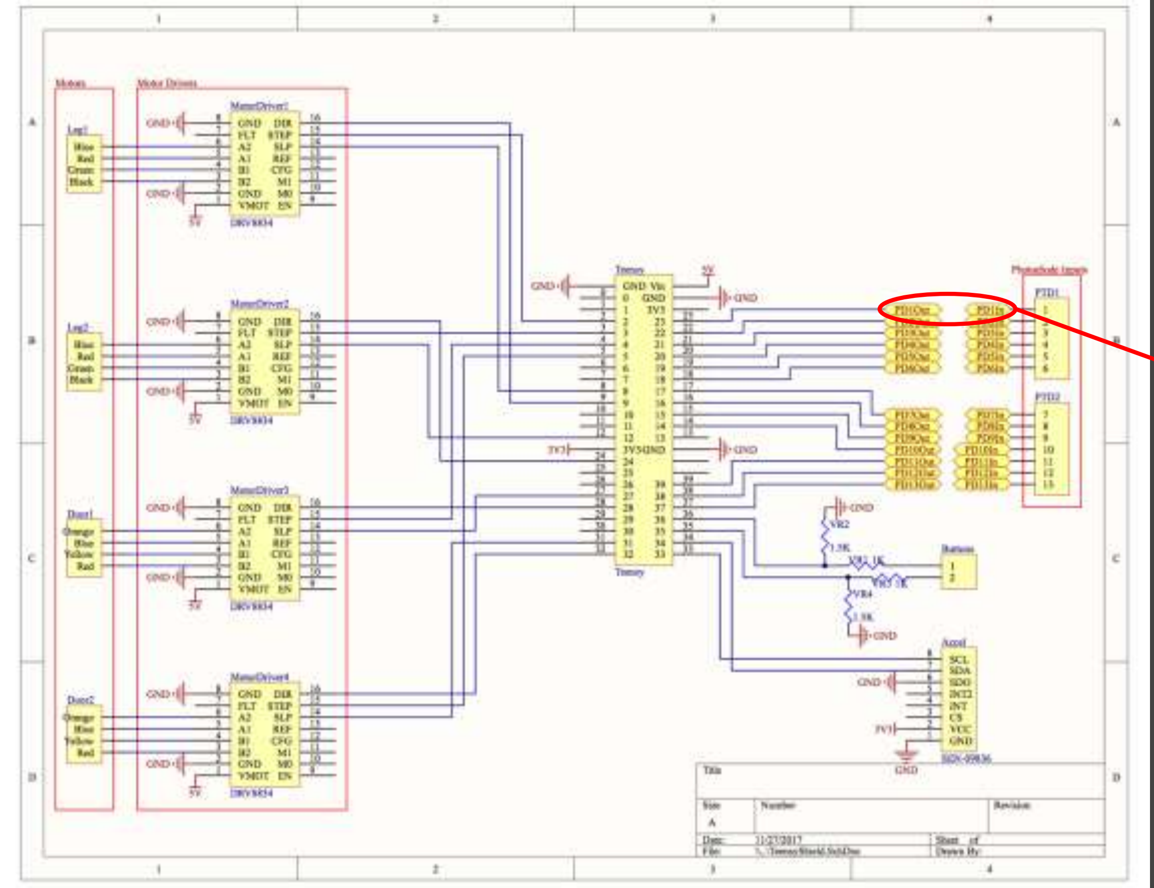
ARS Microcontroller

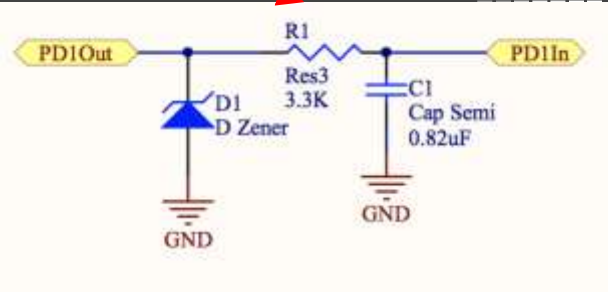
Component	Type/# of Component Pins	Pins on Teensy
Motor Drivers (x4)	Digital/4 (x4)*	6-12 and 24-32
	PWM/1 (x4)	2-5
Buttons (x2)	Digital/1 (x2)	35-36
Accelerometer	SPI/2	33-34
Photodiodes (x13)	Analog/1 (x13)	14-23
Door Command	Digital/1	0
Data Transmit	Serial/1	USB

* Note: 2 pins on each motor driver can be permanently set and do not require connection to Teensy reducing total pins required to 8



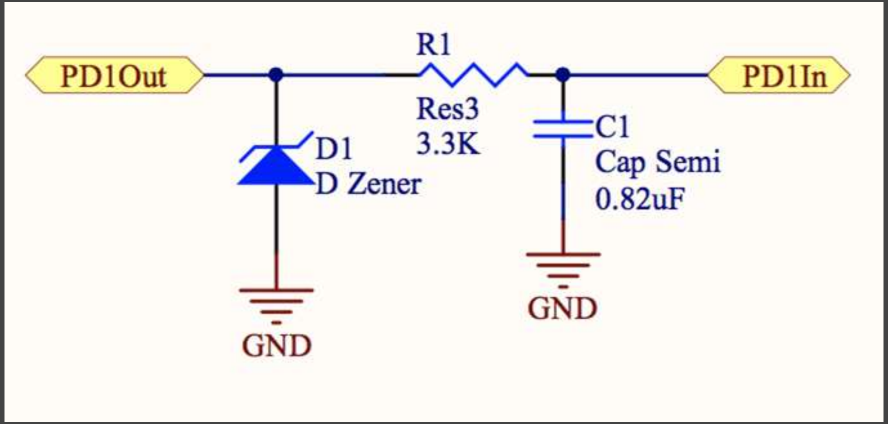
ARS Teensy Shield





ARS Photodiode Noise

- Photodiode, amplifiers, and transmission wires will create noise in signal.
- To reduce noise, low-pass filters were added to the design to remove random noise.



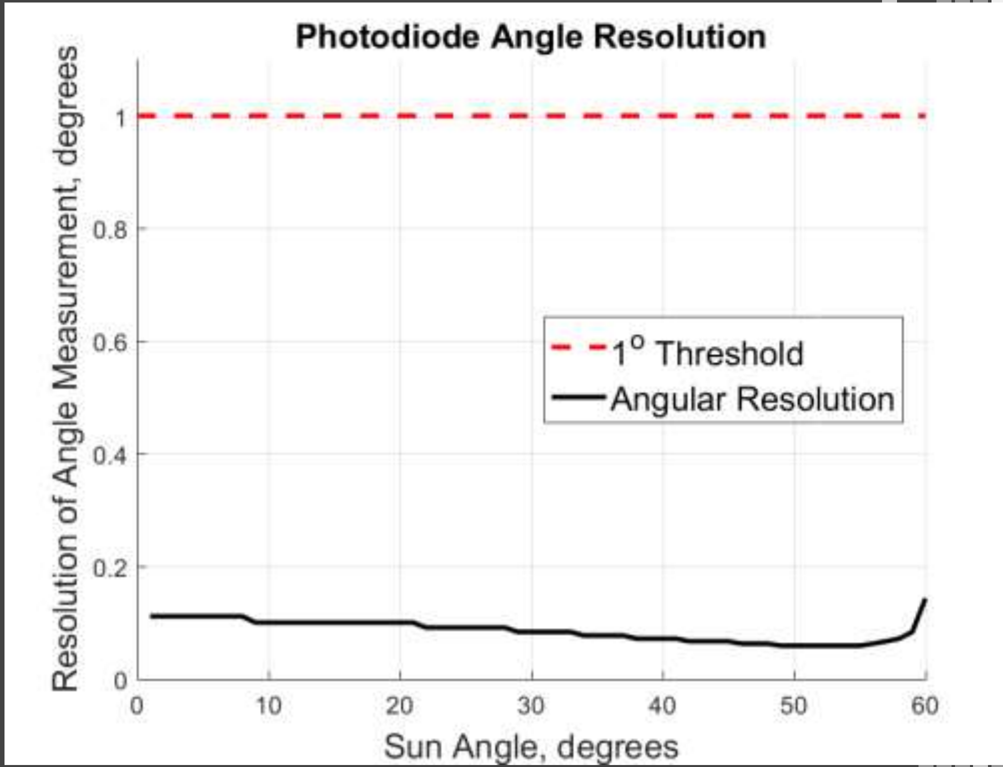
ARS Requirements Development

- Due to the 1D tilting design, only the projection of the sun vector onto the X-Z plane must be accurate to within 1 degree
- However, full sky coverage requirement forces us to know sun vector to within 1 degree
    - At +/- Y sides of CubeSat 1 degree of error in full vector is 1 degree of error in projection
- Result is that we must know sun vector to 1 accuracy.

ARS Photodiode Resolution

- Covers restrict field of view to increase resolution
- Resolution must be less than 1° to meet accuracy of 1°
- Assumptions:
  - Background brightness is ¼ Earth maximum
  - Only ¾ of 10 bit ADC range used for angle measurement
  - Voltage at 0° (direct sun) is ADC maximum

Worst resolution 0.15° < 1°



Nominal Design Case – Unfiltered Signal

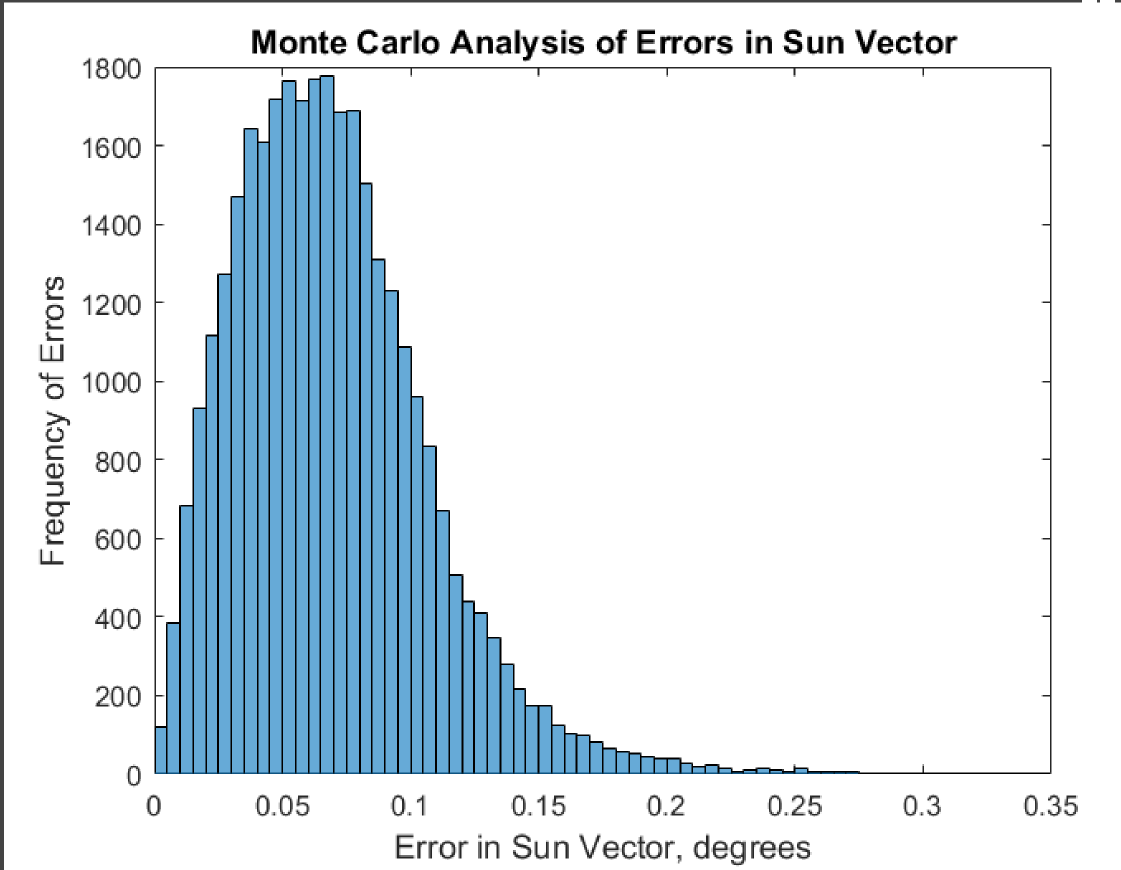
- Varied thermal and sampling noise uniformly
- 30,000 iterations
- Maximum error in sun vector is 0.35°

Worst Errors 0.35° < 1°

↓

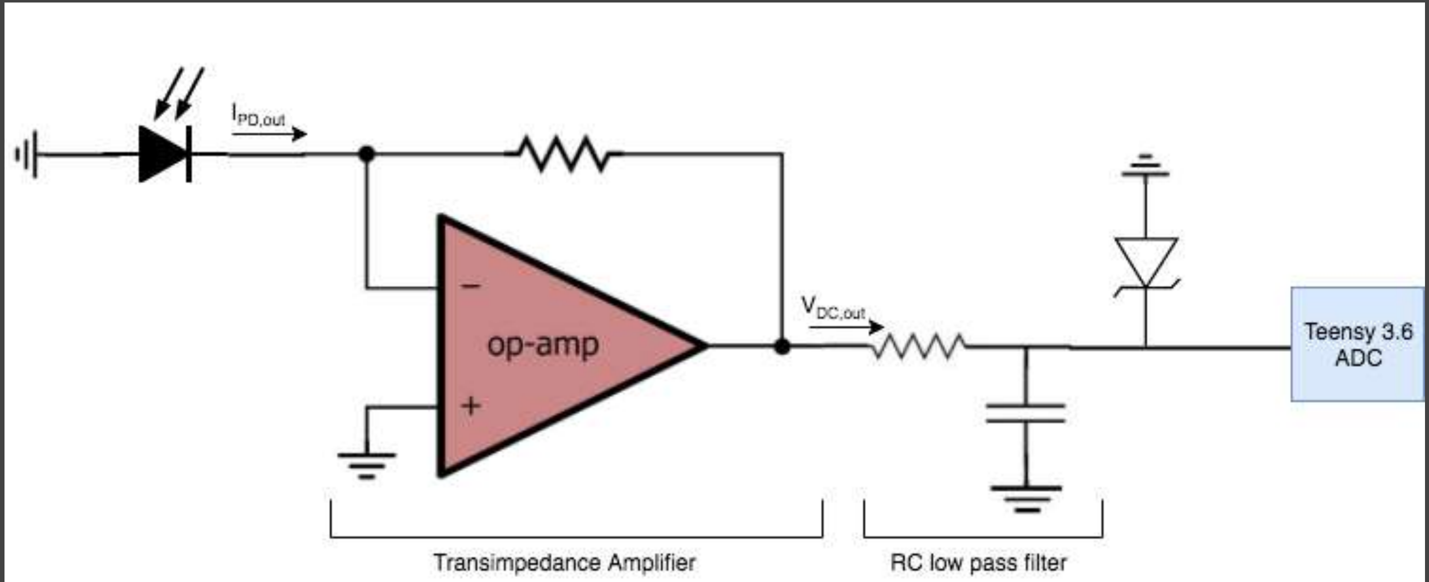
Requirement 3.2.2 satisfied

- However, margin is a concern
- Manufacturing tolerances could push above 1°



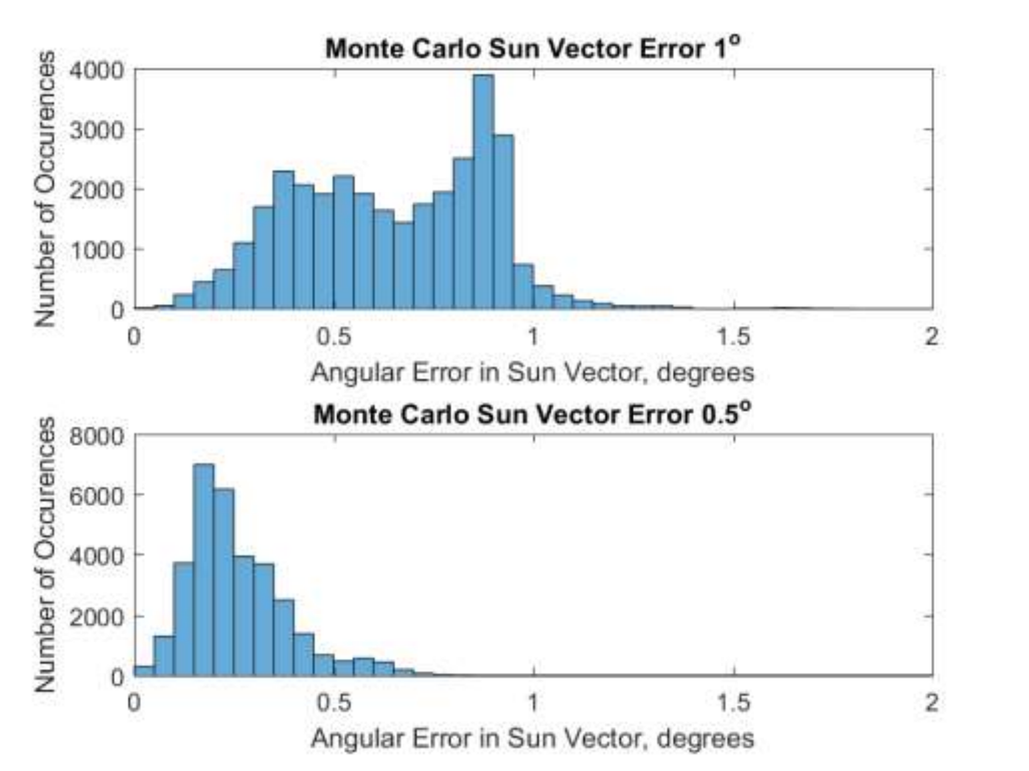
ARS Photodiode Signal Processing

- Transimpedance amplifier
  - Converts current to voltage and amplifies signal
- RC low pass filter: R = 3.6kΩ, C = 0.82uF
  - Filters signals $F_c \geq 51.4$Hz (filters lab environment noise at 60Hz)



Off-Nominal Design Case

- Photodiodes won't be mounted perfectly
- Knowing position improves accuracy
- ARS component level testing will allow us to find these errors

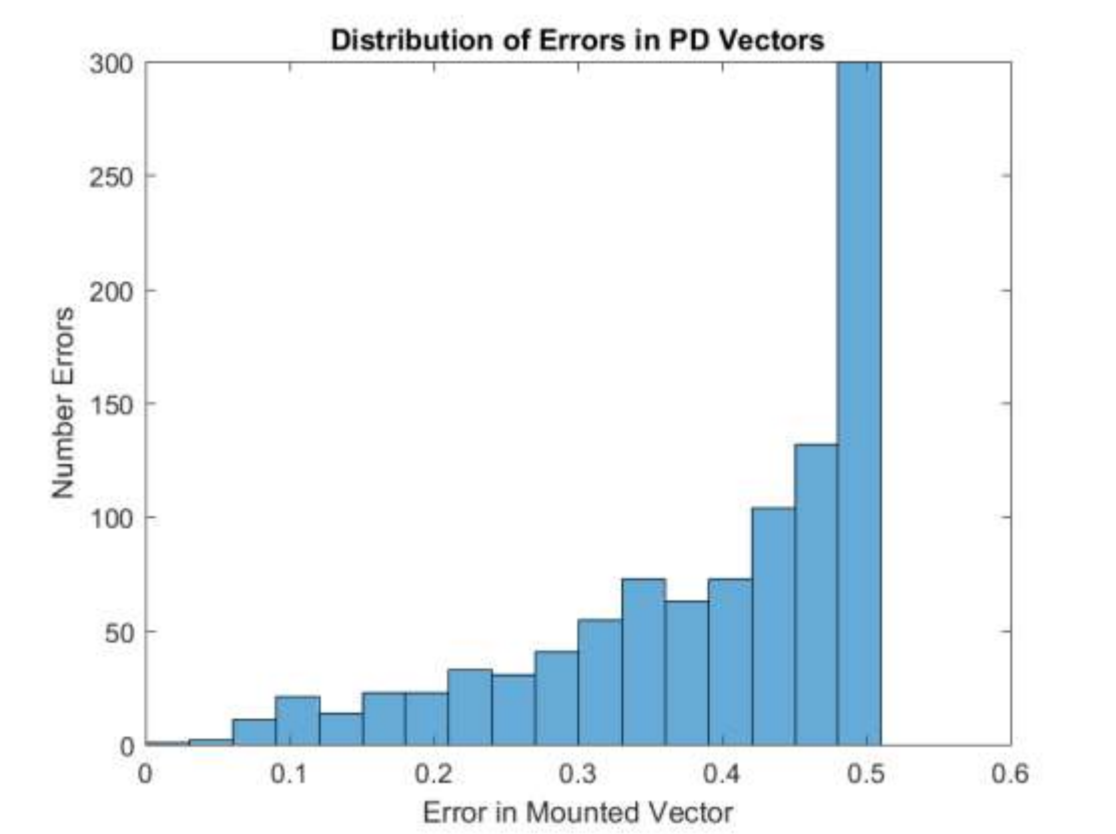


Worst Errors 0.75° < 1°

Requirement 3.2.2 satisfied

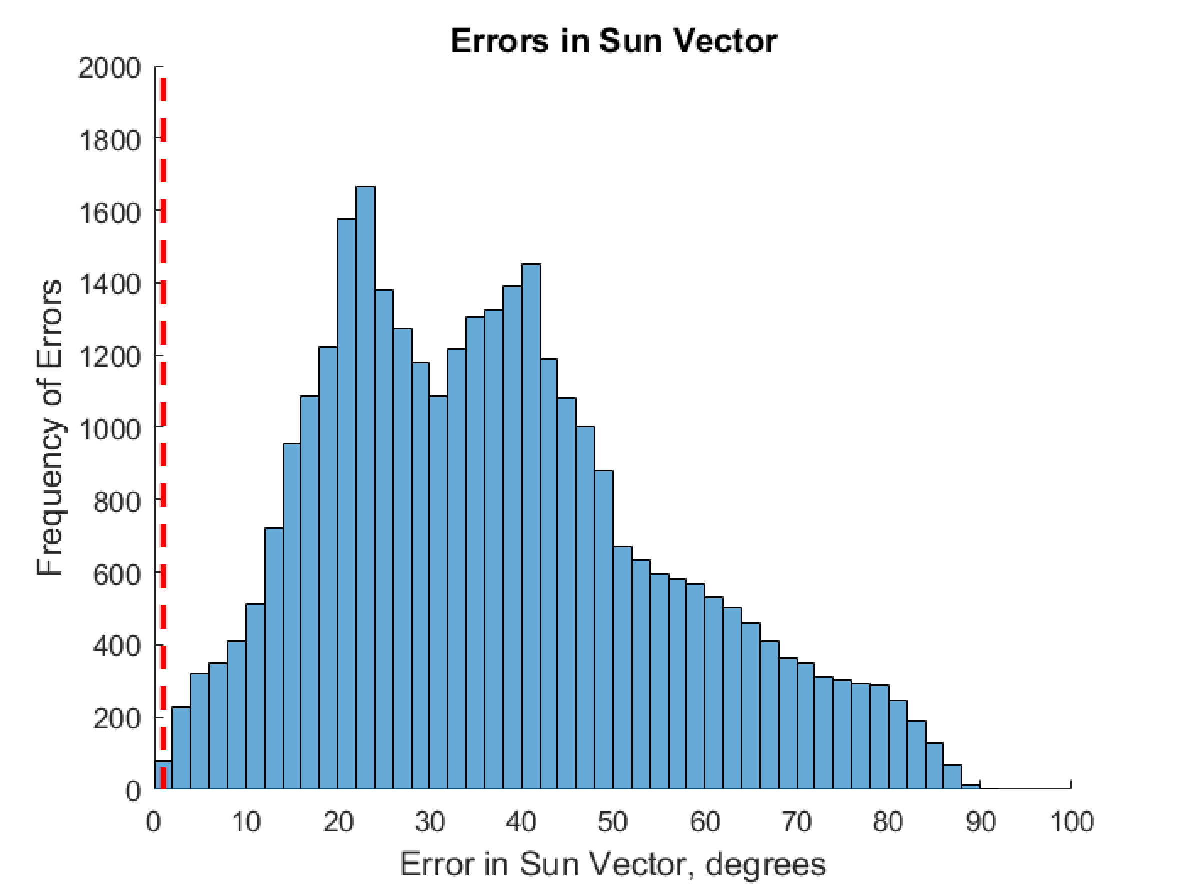
Off-Nominal Design Case

- Distribution of Errors in Off-Nominal simulation
- Difficulty making a 'good' distribution



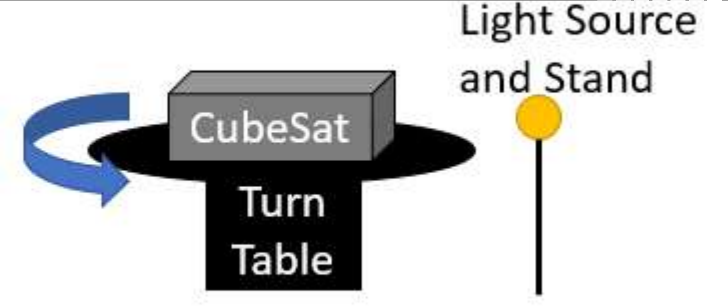
Off-Nominal Design Case

- We are having issues correctly modeling the error from photodiode covers
- Minute (0.0005 mm) changes in manufacturing tolerances cause outrageous errors
  - Sun angle
  - Photodiode Voltage
- Two Options:
  - Off ramp to which side is sunnier
  - Calibrate out photodiode cover error



ARS Photodiode Mounting

- Photodiodes will not be placed with perfect angular position
- Need to maintain sun vector determination accuracy
  - Full CubeSat will be calibrated against photodiode mounting errors
  - QB50 turntable can report position to 0.5 degrees
  - Interfaces with a control computer to report position
  - Can find mounting to within 0.5



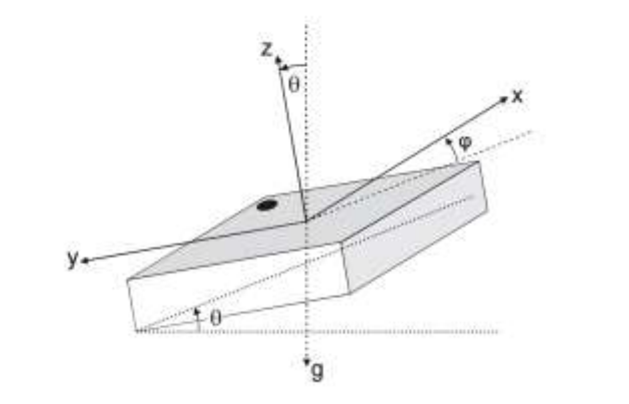
Tilt Sensor Design

Why?

- Closed loop actuation requires **independently** measured tilt angle.

How? - ADXL345 Digital Accelerometer

- Three axis tilt
  - Negates any mounting error
- Digital output reduces electrical noise
- If baseline is tilted 45 degrees
  - **Accurate to 0.32 degrees**



Tilt Sensor Mounting Error

Why?

- Improper mounting of the accelerometer can provide erroneous data.

How? - Calibration and Algorithm choice

- Single vs double vs triple axis algorithms
- Mounting error can be significant using two axis algorithm
- Mounting error can be accounted for using three axis algorithm
    - Can input additional noise if Z axis is noisy

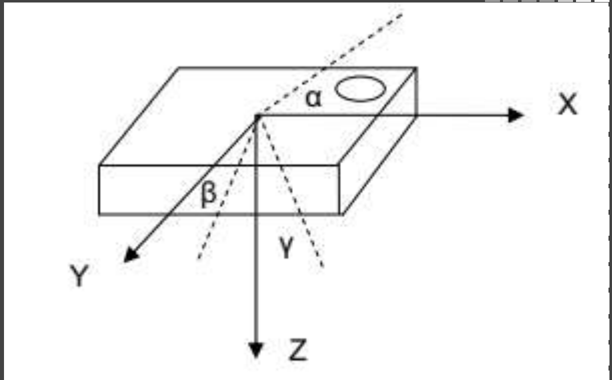
Tilt Sensor Algorithms

Why?

- Reduce error from mounting and signal noise

How? - Algorithm choice

- Single vs double vs triple axis algorithms



$$\alpha = \arcsin\left(\frac{A}{g}\right)$$

$$\alpha = \arcsin\left(\frac{A_{x1}}{g}\right)$$

$$\beta = \arcsin\left(\frac{A_{y1}}{g}\right)$$

$$\text{Pitch} = \alpha = \arctan\left(\frac{A_{x1}}{\sqrt{(A_{y1})^2 + (A_{z1})^2}}\right)$$

$$\text{Roll} = \beta = \arctan\left(\frac{A_{y1}}{\sqrt{(A_{x1})^2 + (A_{z1})^2}}\right)$$

Tilt Sensor Noise Analysis

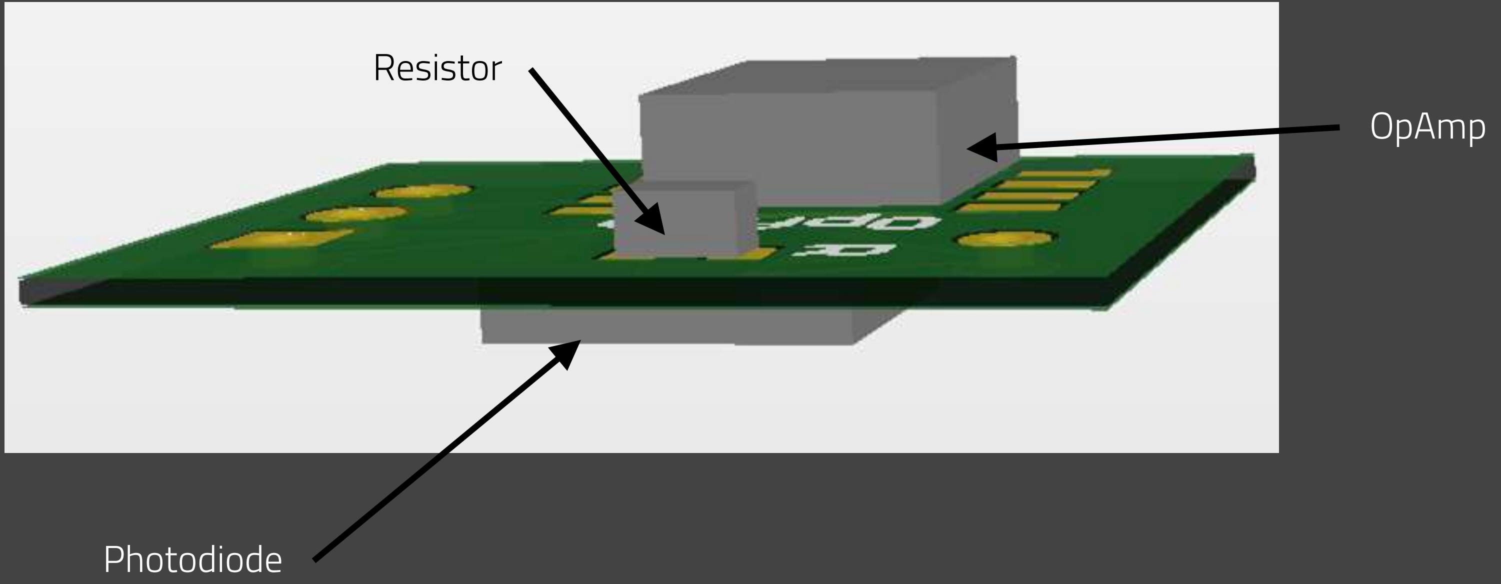
Why?

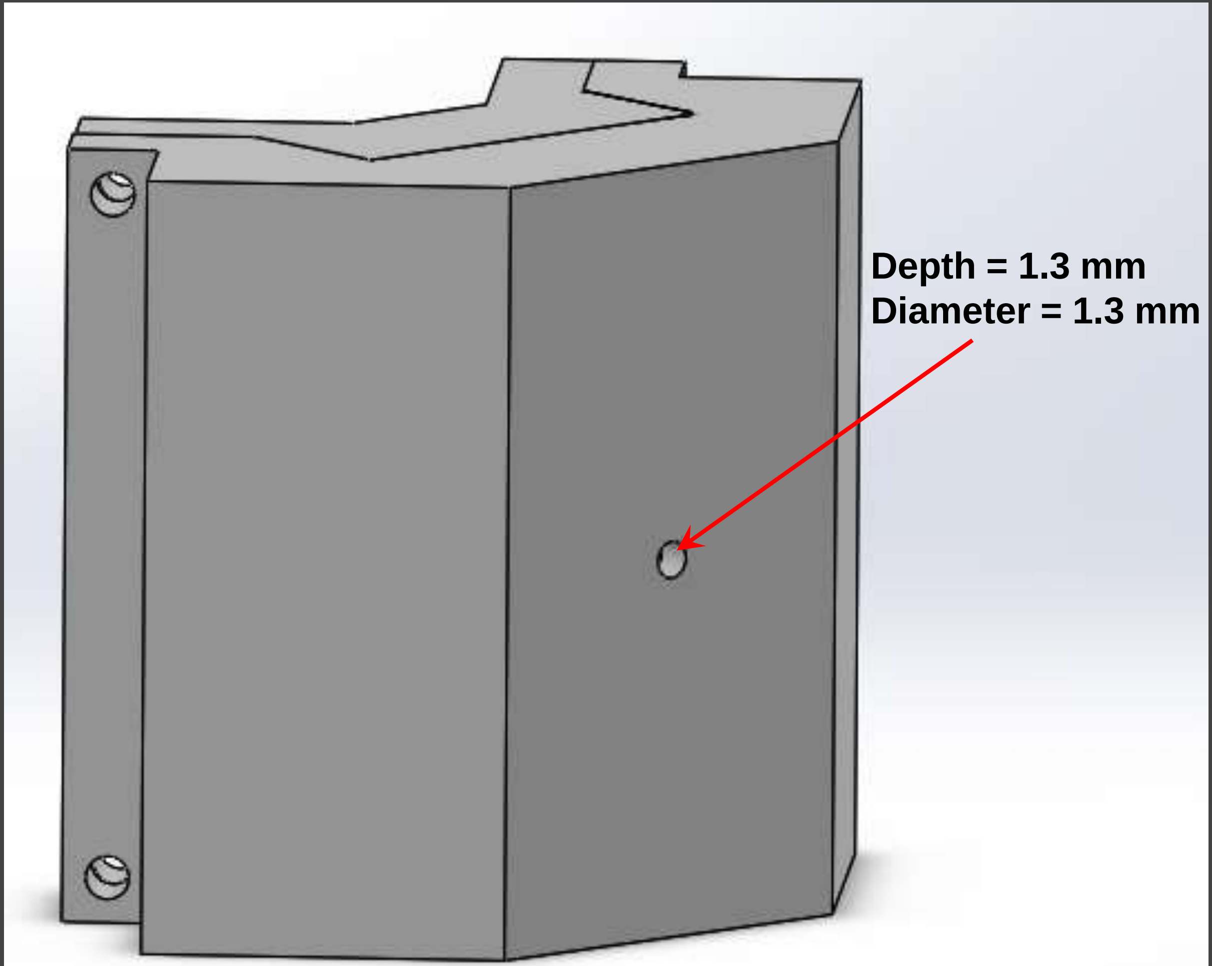
- Internal noise must be low enough to resolve 1 degree changes

How? - Standard deviation and range of two and three axis algorithm

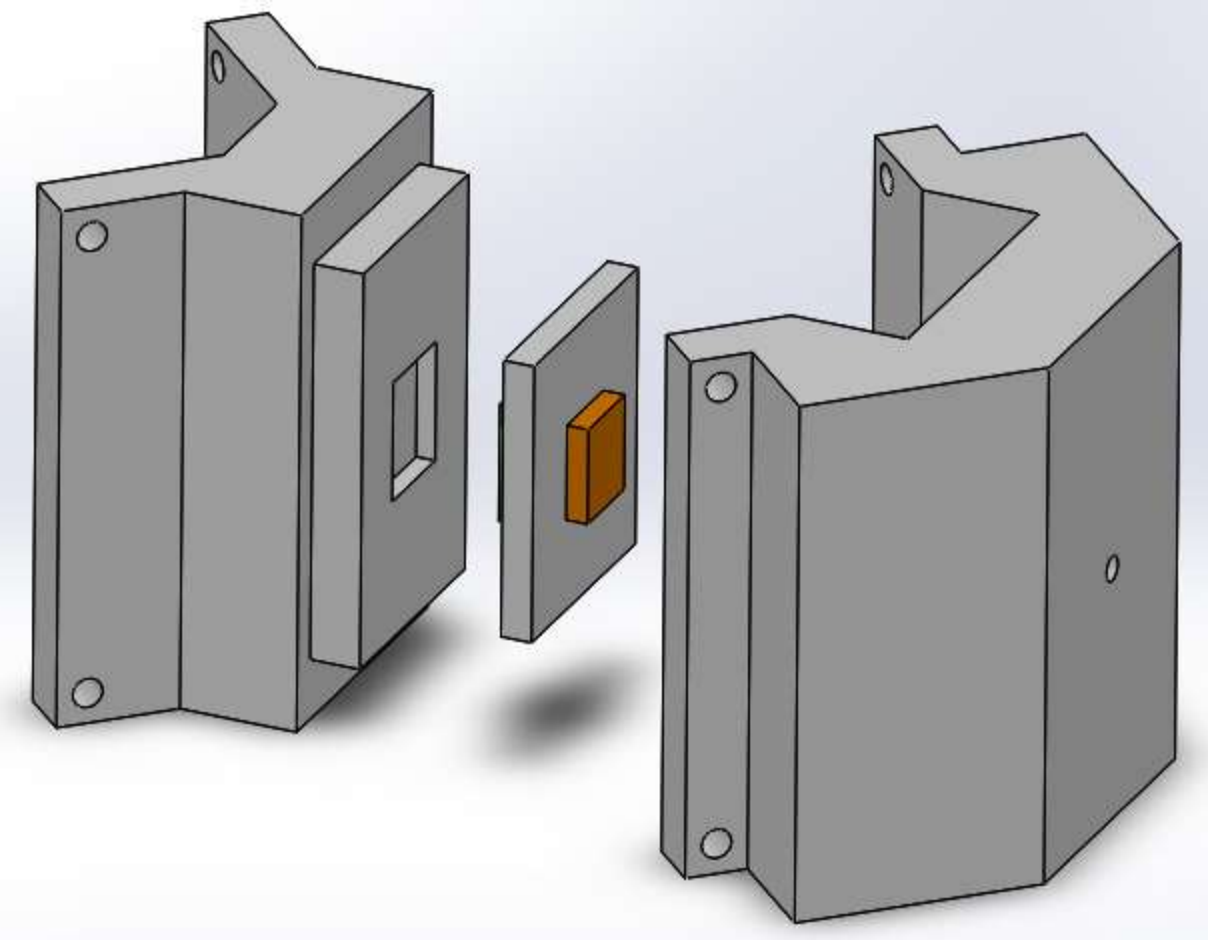
Algorithm	Two Axis Algorithm		Three Axis Algorithm	
Angle	Pitch	Roll	Pitch	Roll
Standard Deviation (degrees)	0.11	0.11	0.28	0.28
Range (degrees)	0.67	0.447	1.74	1.14

ARS Photodiode Board

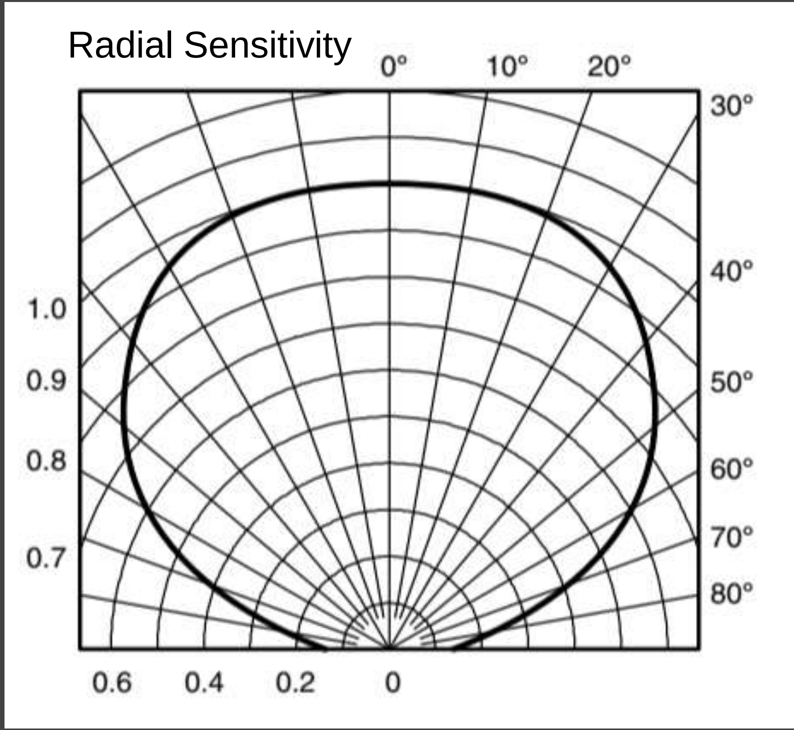


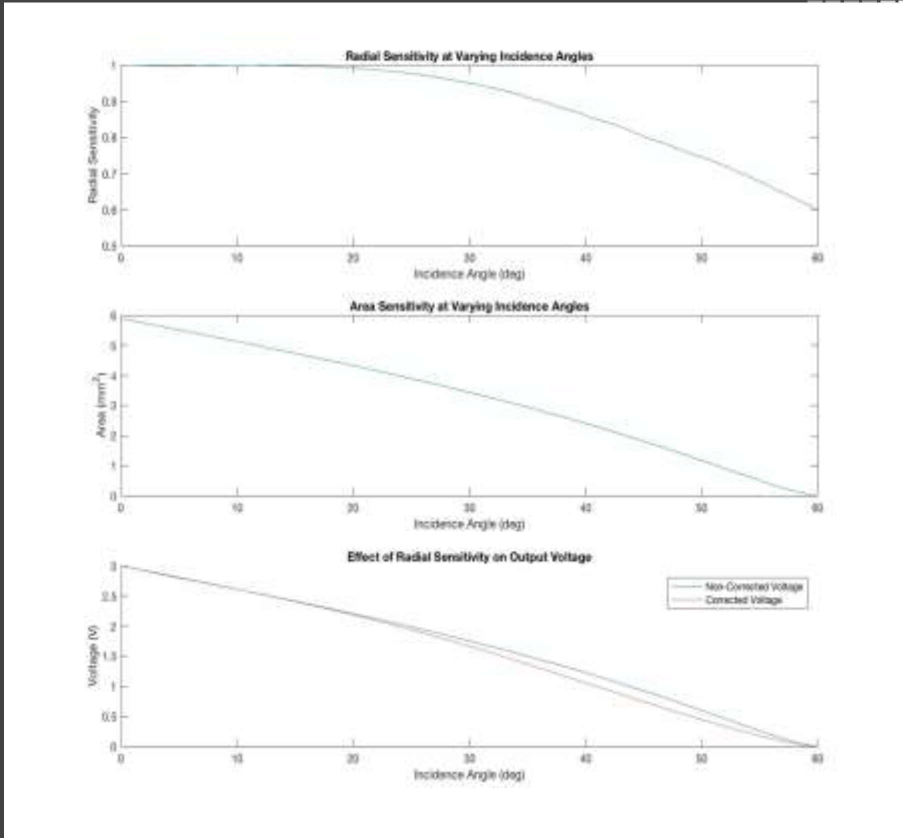


Photodiode Edge Cover



ARS Photodiode Sensitivity



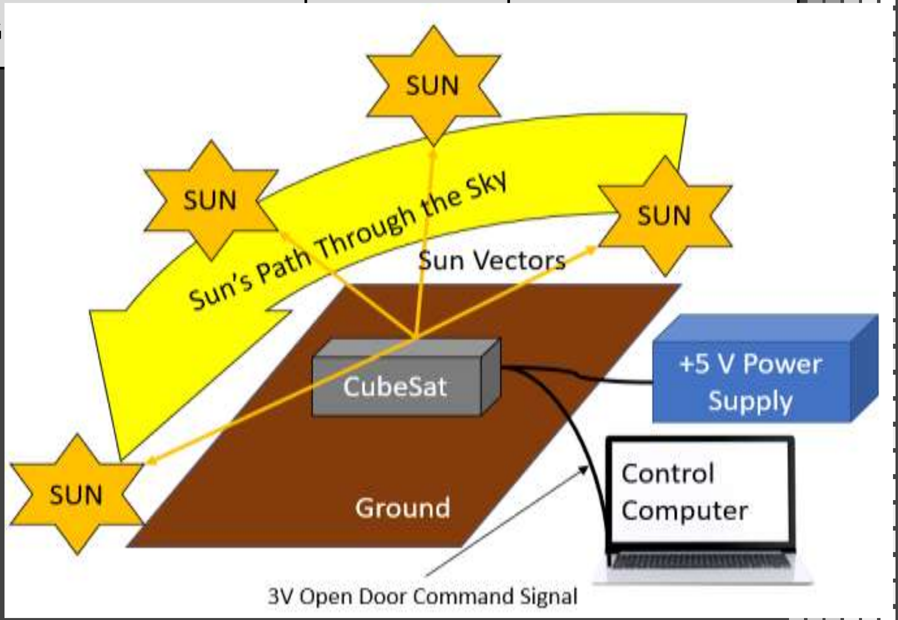


ARS Sun Determination Test

Objective	Compare ARS sun vector to actual vector
Date	March 5th - March 18th
Location	Outside, top of building
FR Verified	FR3: The ARS and mechanisms shall open the instrument door that is pointing away from the sun. FR6: The software shall be capable of data processing, detecting dust events, and running ARS algorithms.

Equipment Needed	Procurement
ARS System	Built
5V Power Supply	Borrowed
Computer & STK	Owned

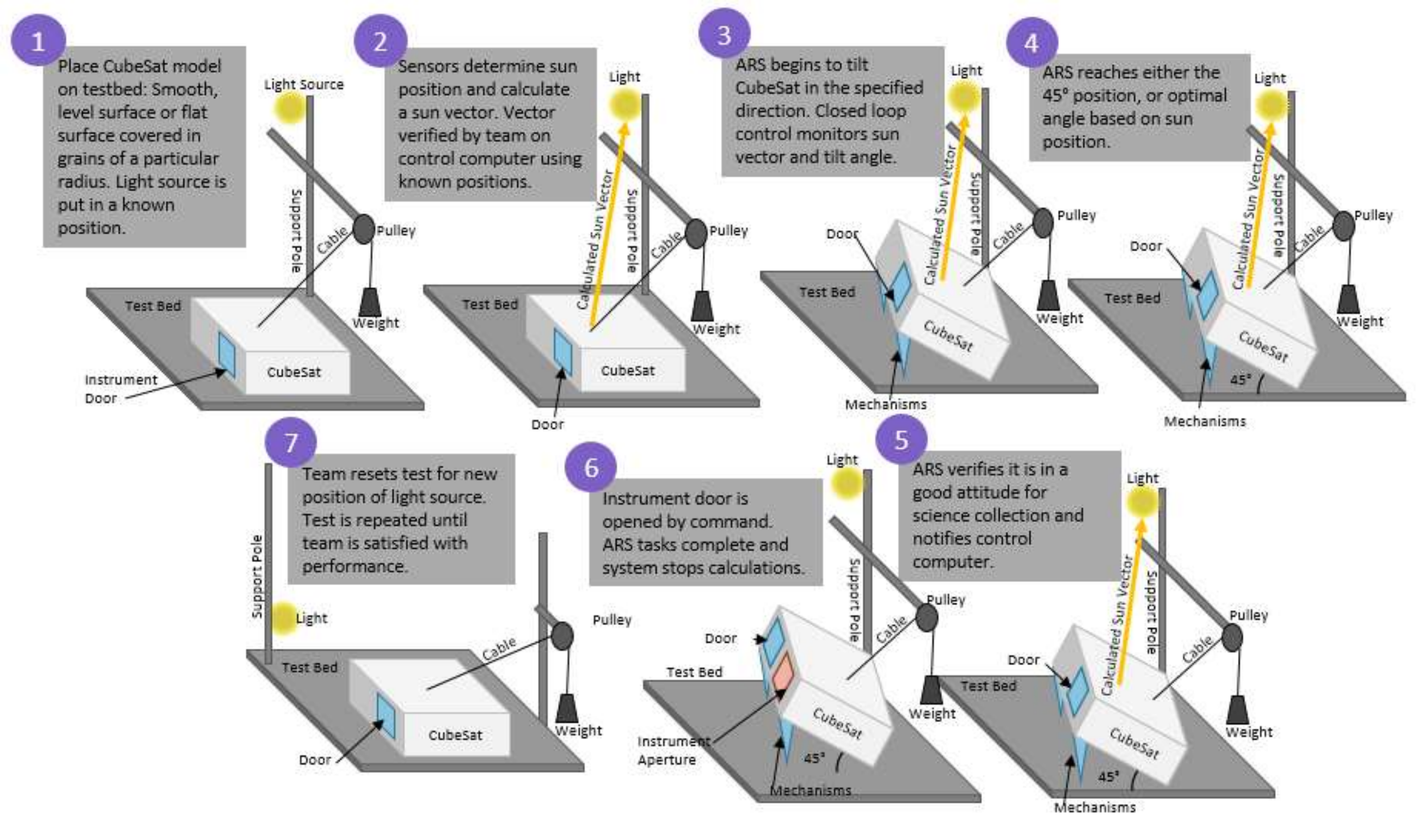
Data Needed	Resolution	Sampling Rate
Measured Sun Vector	1°	Every 10 Minutes
STK Sun Vector		Every 10 Minutes
G		



ARS System Level Tests

- Test photodiodes outdoors over a longer duration to ensure sun vector calculations are correct
- Errors in initial position can be accounted for over the test duration.
- Sun's movement will test multiple places in the sky for the Sun sensing system.
- Known sun vector can be found using STK software package.

ARS Test ConOps



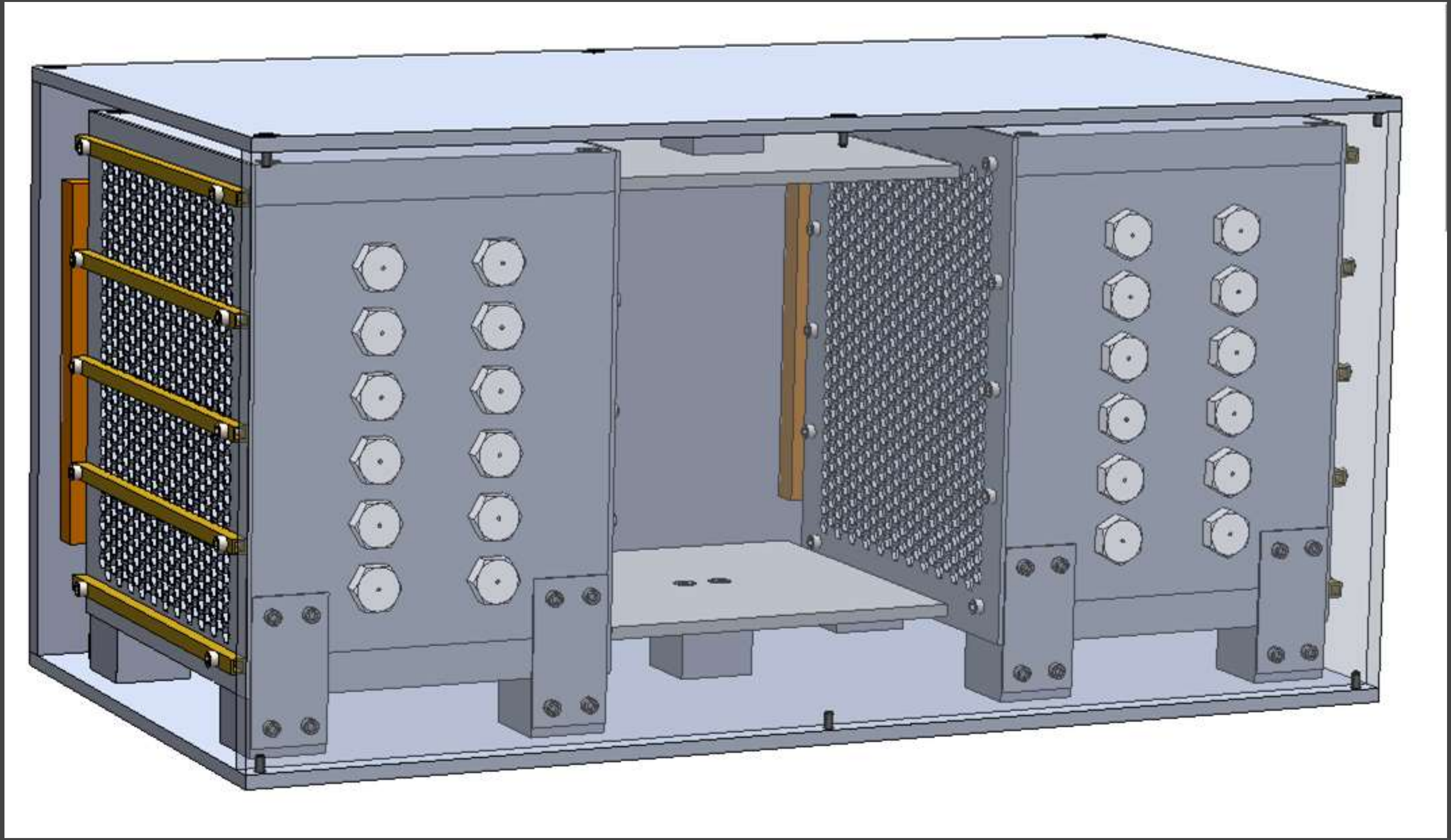
ARS Accelerometer

- Component Test
  - Attach accelerometer to CNC mill
  - Move CNC by precise amount
  - Measure change in angle
  - Compare to accelerometer reading
- Systems Test
  - Acuate Cubesat to a commanded angle
  - Measure using protractor
  - Compare actual angle to measured angle

Instrument

Q, v, m calculation; DFR bias; and election deflection

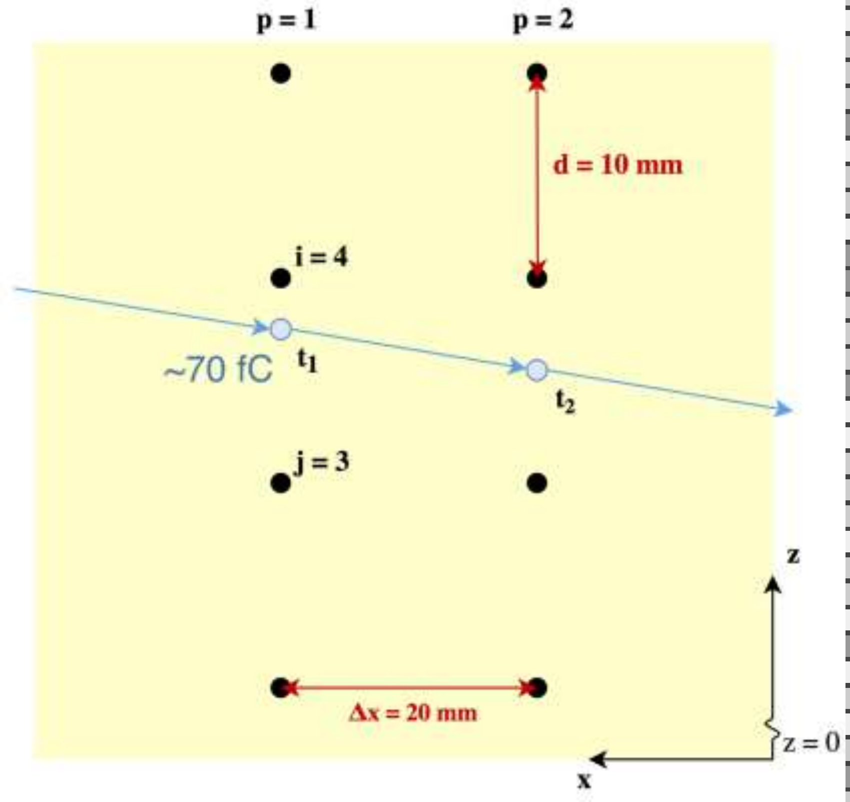
Instrument Verification



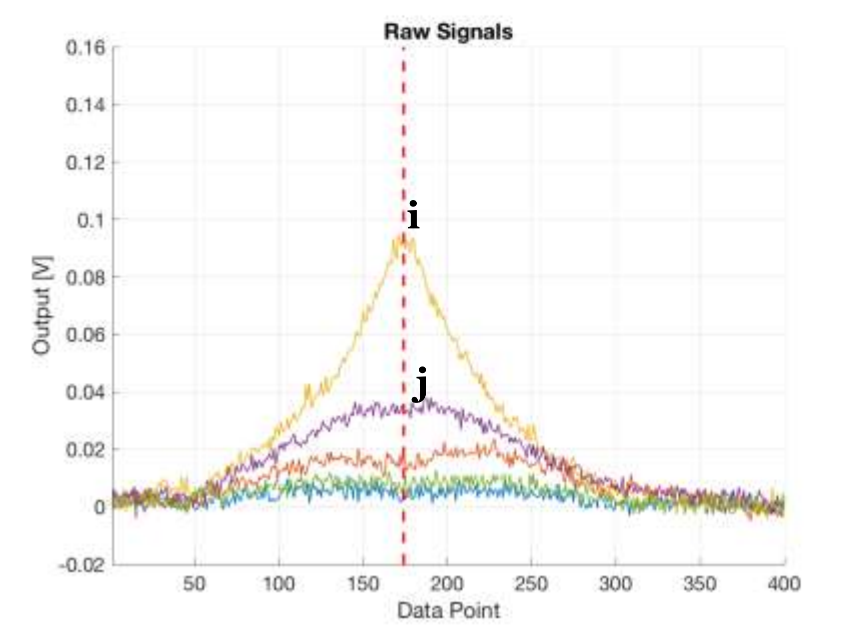
Methods for Q, v, & m extraction

- Definitions:
  - p ~ plane number
  - n ~ wire number in given plane
  - i ~ wire w/ highest voltage
  - j ~ wire w/ 2nd highest voltage
  - t_p ~ time particle crosses plane p
  - d ~ wire spacing
  - Δx ~ plane spacing
  - h_n ~ z-coordinate of wire n
  - q_n ~ charge induced on wire n
  - V_n ~ voltage signal from wire n
  - ρ ~ CSA sensitivity

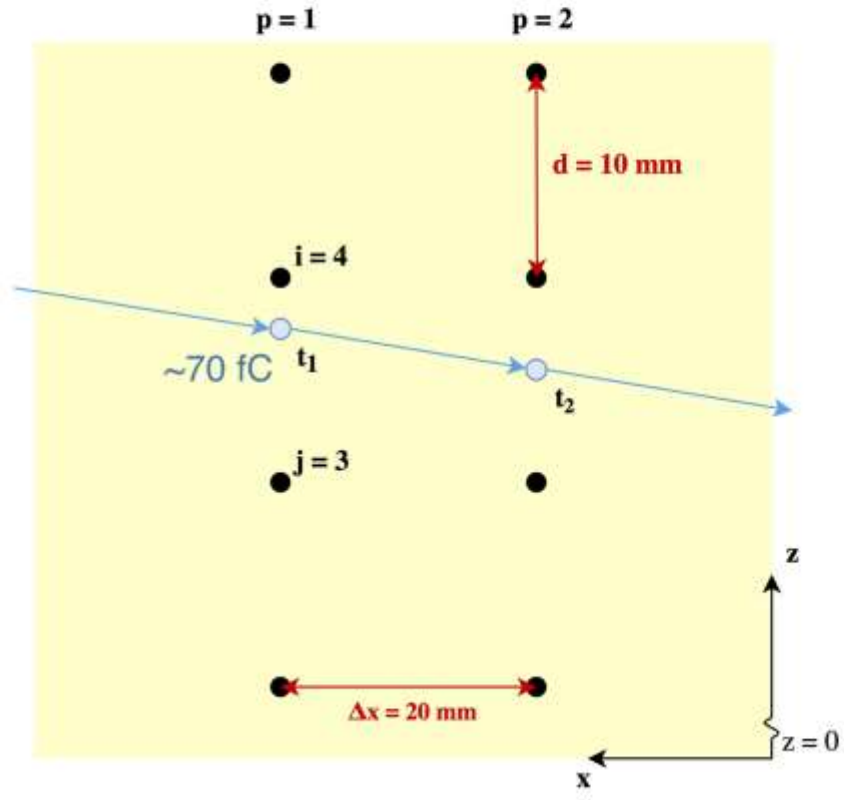
DTS Unit (sub-section)



Methods for Q, v, & m extraction



DTS Unit (sub-section)



- Charge Sensitive Amplifier (CSA) creates voltage from induced charge:
  - Sensitivity: ρ =18 mV/fC

Methods for Q, v, & m extraction

- Key assumption: when particle crosses a wire plane the induced charge is only on the wires in that plane

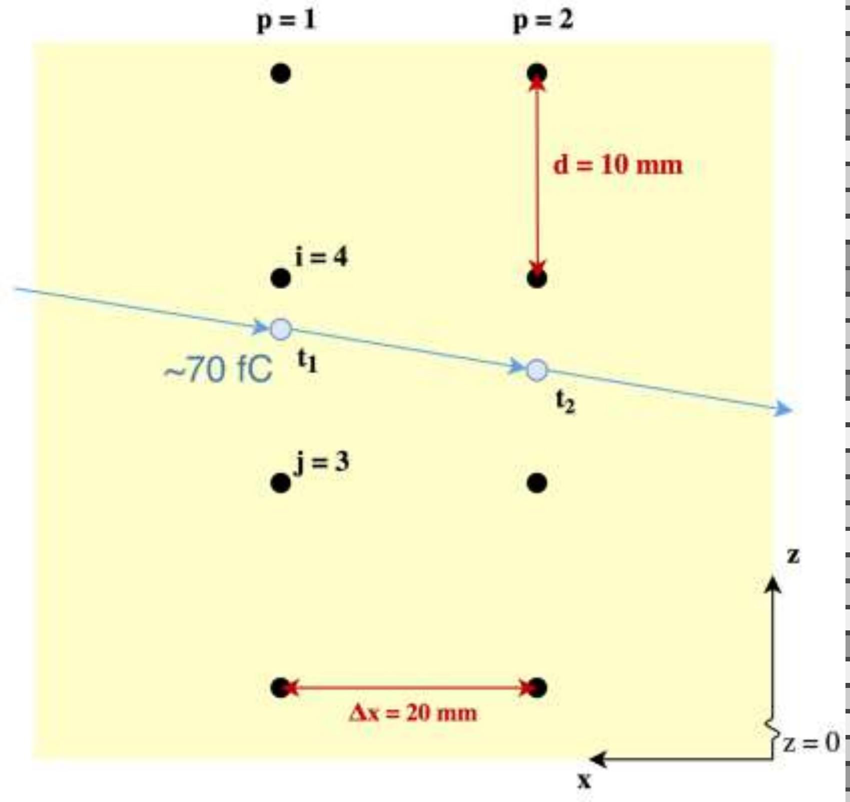
Steps:

1. Q calculation (@ $t = t_1$)

$$Q = \rho \sum_{n=1}^{6} V_n$$

n ~ wire number (in plane)

DTS Unit (sub-section)



Methods for Q, v, & m extraction

Steps (Cont.):

2. Distance from closest wire

$$d_i = \frac{d}{1 + V_i/V_j}$$

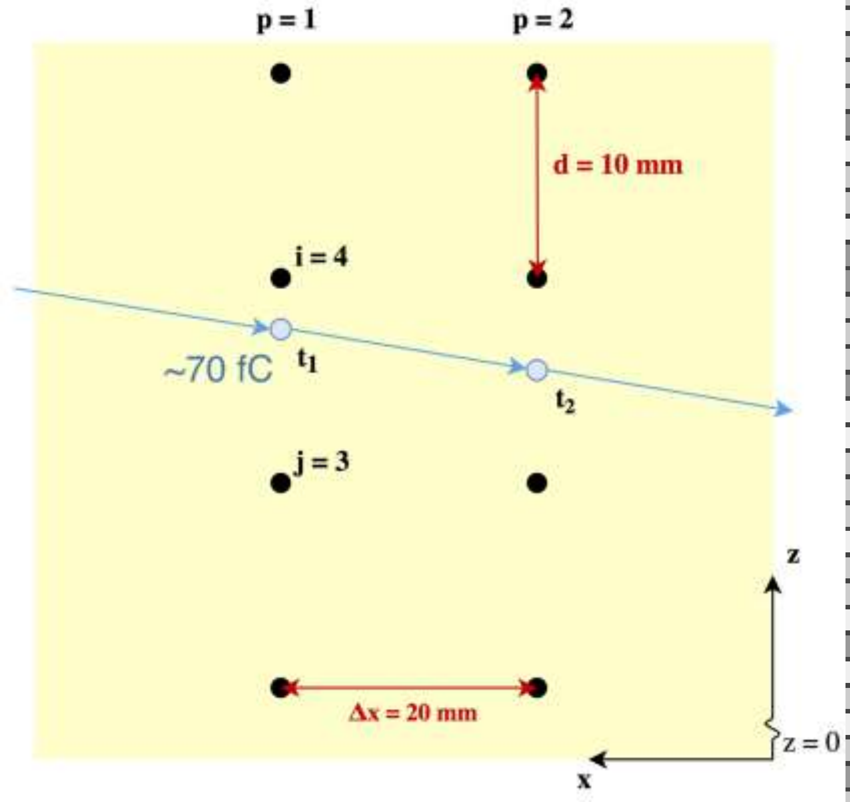
2. Absolute z-coordinate

If $i > j$	→	$z_p = h_i - d_i$
If $i < j$	→	$z_p = h_i + d_i$

2. Repeat steps 2 & 3 for every plane

   (p = 1⟶ 4)

DTS Unit (sub-section)



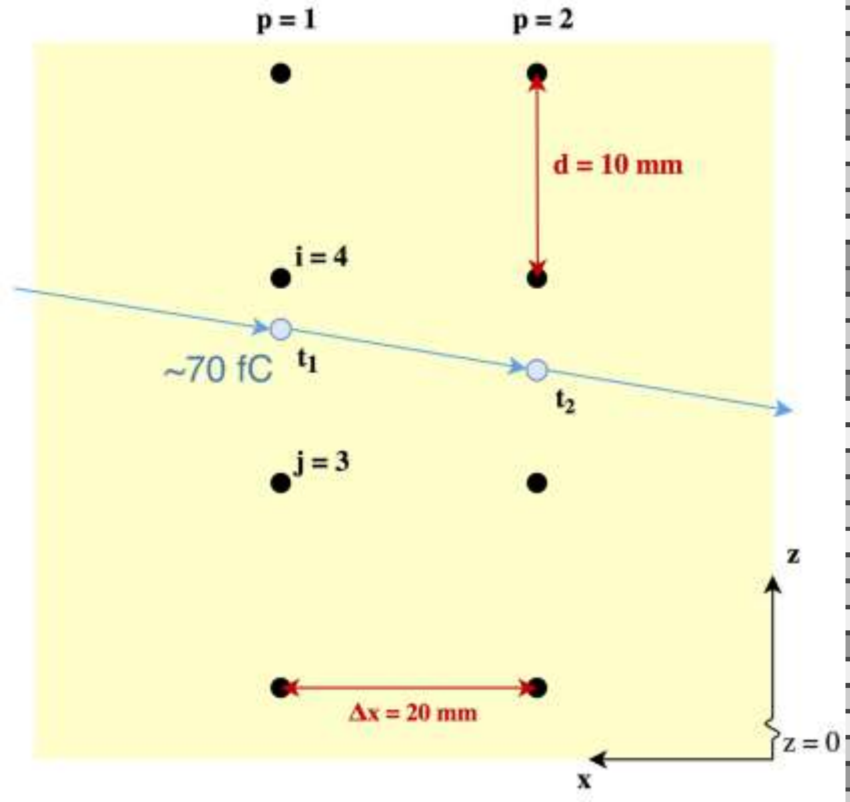
Methods for Q, v, & m extraction

Steps (Cont.):

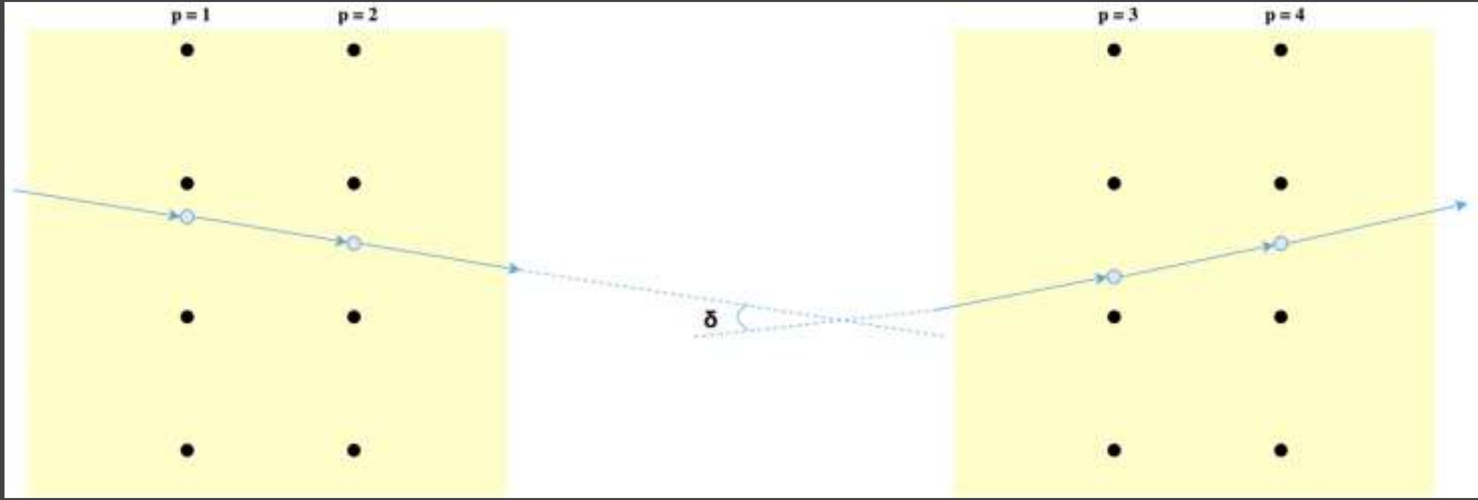
5. Velocity calculation

$$v = \frac{\sqrt{(\Delta x)^2 + (z_1 - z_2)^2}}{t_2 - t_1}$$

DTS Unit (sub-section)



Methods for Q, v, & m extraction

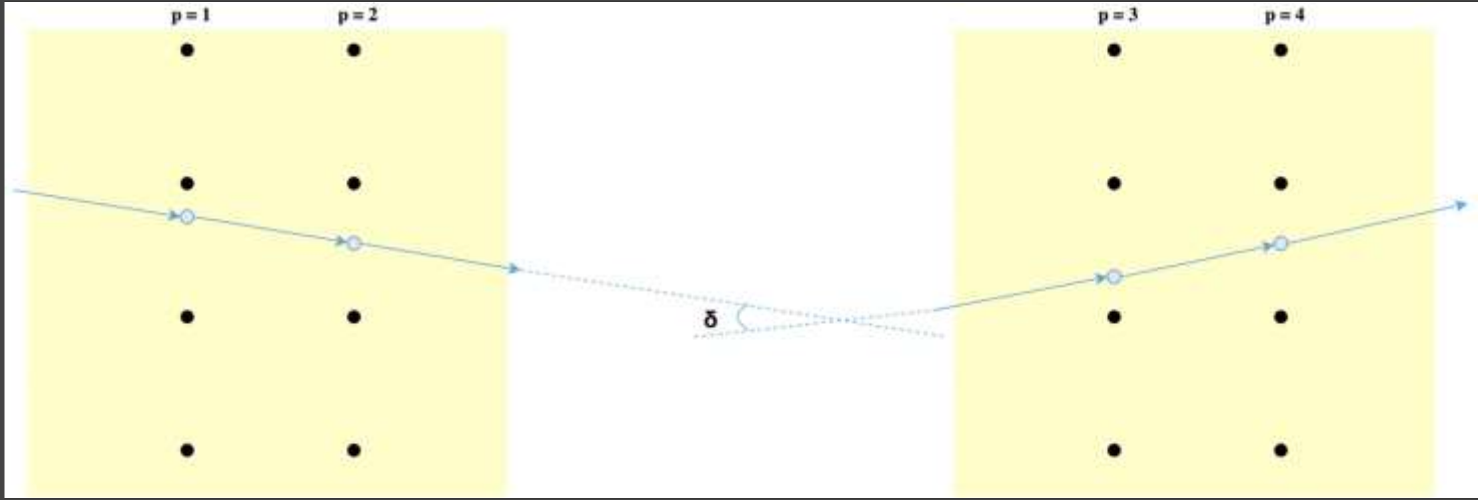


Steps (Cont.):

6. Calculate turning angle δ

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

Methods for Q, v, & m extraction



Steps (Cont.):

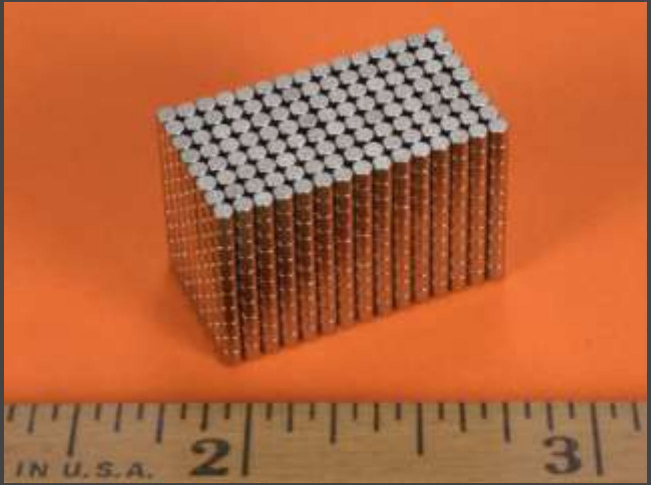
7. Calculate mass (where l = 0.07 m is the length of the deflection region)

$$m = \frac{QEl}{v^2 \tan(\delta)}$$

Electron Deflection

Cylindrical magnets:

- D = 1.59 ± 0.10 mm
- t = 1.59 ± 0.10 mm
- Magnetic Remanence:
  - B_r = 1.48 T

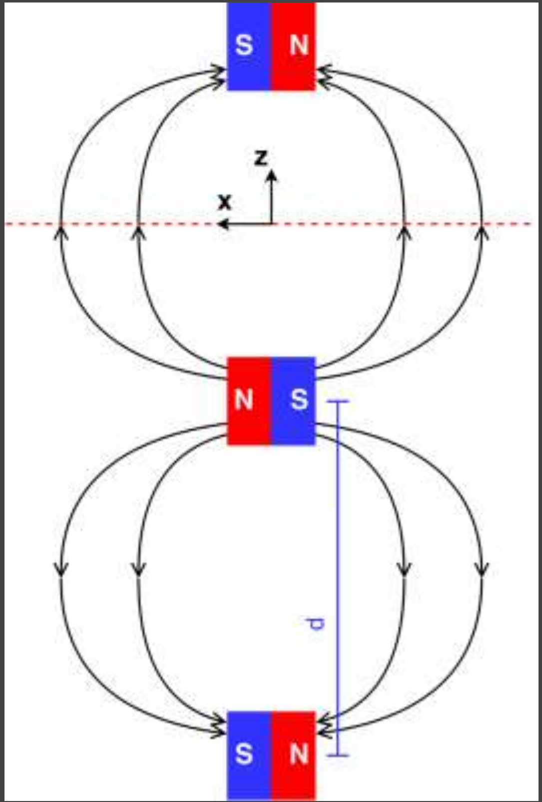


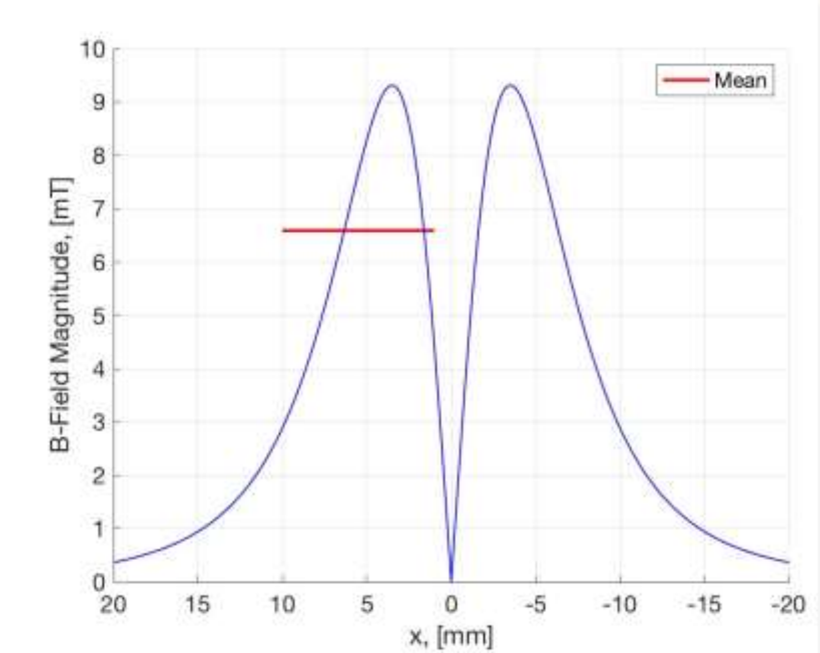
- Need to prove gyroradius of 100 eV electron to be sufficiently as to not penetrate the instrument more than 1 cm (first wire plane)
- Gyroradius:

$$r_q = \frac{mv}{qB}$$

Electron Deflection

Using 5 magnet bars: d = 17.5 mm





From 10 → 1 mm: $B_{mean} \approx 5.3$ mT

$r_q \approx 6.3$ mm
(e^- gyroradius)

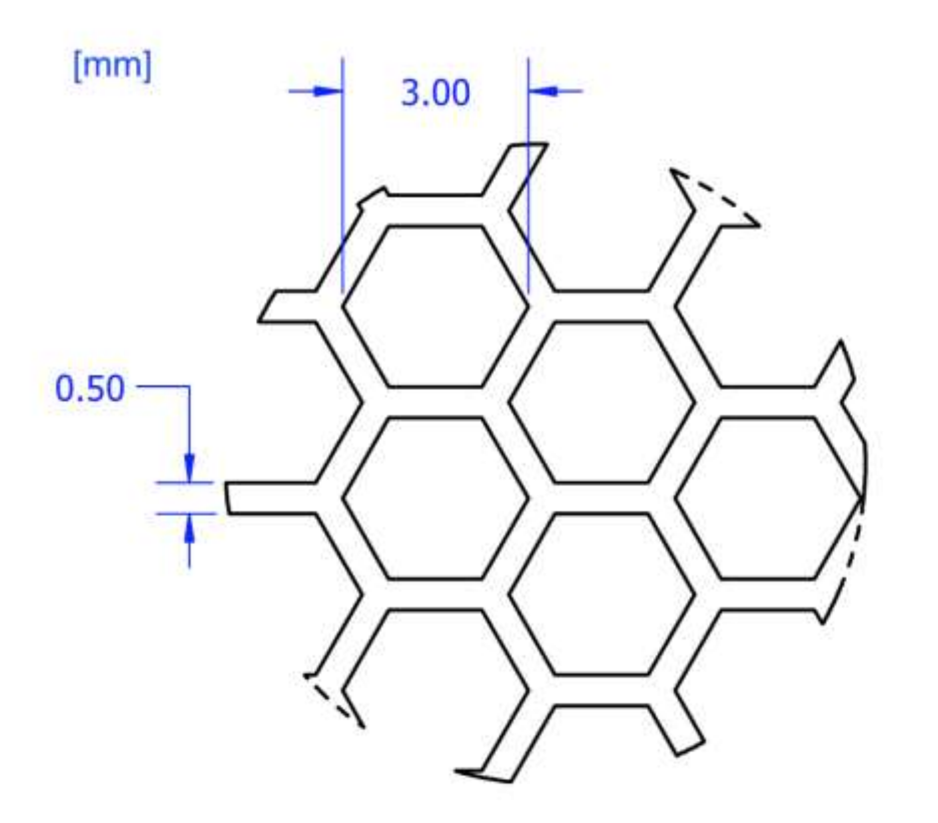
Mesh Grid Design

Why?

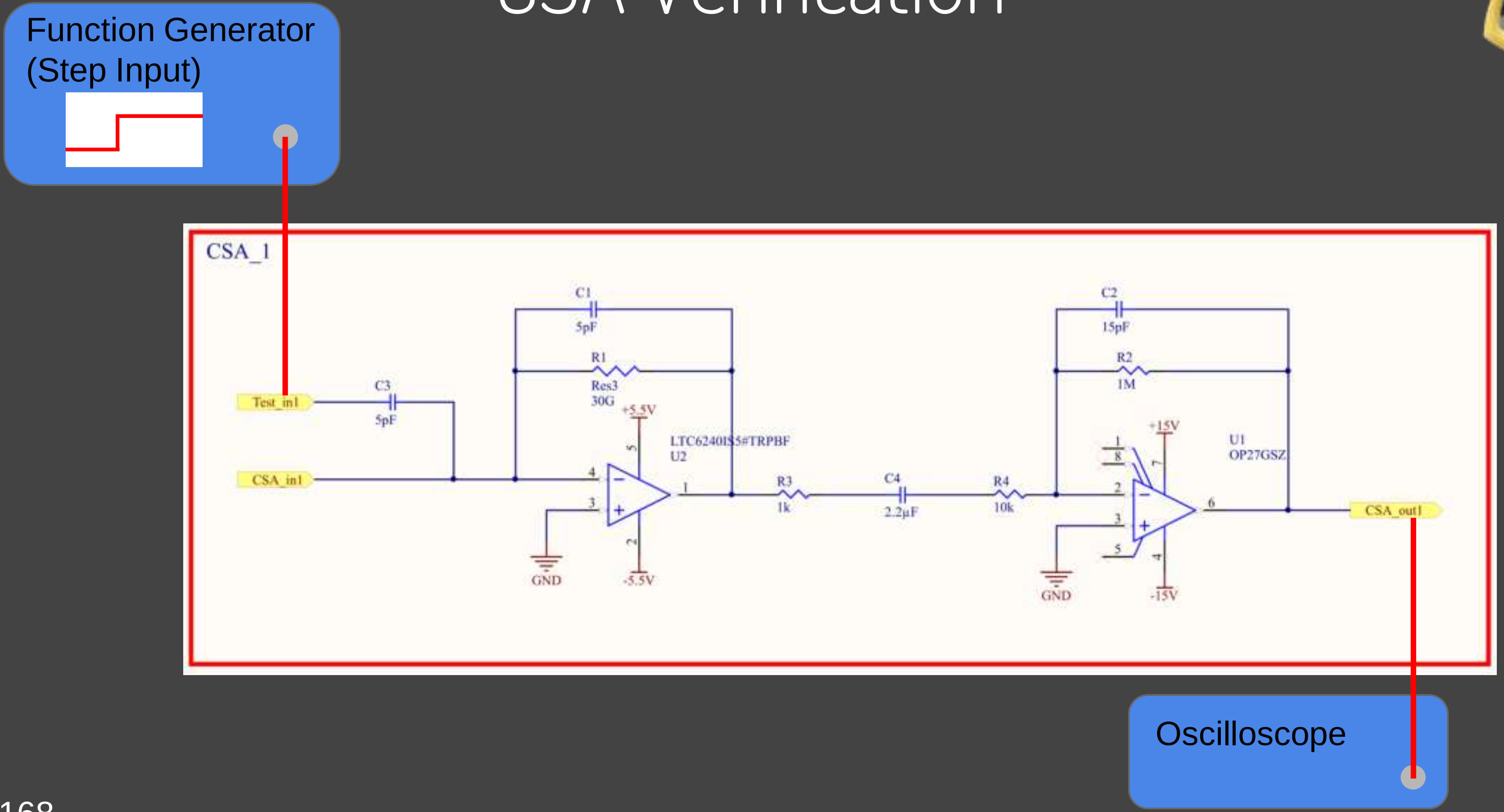
- Fully enclose DTS in a Faraday cage to reduce noise in wire electrodes

How?

- 20 Ga Aluminum Sheet
- Perforated hexagonal pattern cut into sheet
- Plan to have custom laser cut professionally
- 67% open area



CSA Verification



CSA Verification

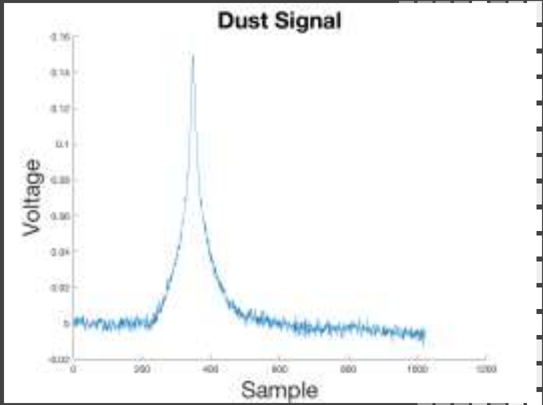
Objective	Verify CSA circuit is function and its sensitivity
Date	February 5th - 9th
Location	IMPACT Dust Lab **OR** ITLL

Equipment Needed	Range	Resolution	Procurement
Function Generator (Step)			Borrowed
Oscilloscope			Borrowed
CSA Circuit Board	-	-	Built
Data Needed	**Range Needed**	**Resolution Needed**	**Sampling Rate**
Input Voltage	0 - 50 mV	1 mV	1 kHz
Output Voltage	0 - 3.3 V	20 mV	1 kHz

Instrument Testing (Post-Assembly)

Once assembled:

1. Connect to lab computer and output live voltage readings from wire electrodes (LabVIEW)
   - Check for reasonable voltage signals for no charge present
2. Drop charged dust into both ends of the instrument
   - One DTS active
   - Vary locations above the entrance plane
   - Check for reasonable increase in voltage due to charge particles present
3. Record output data from particle events manually
4. Run trigger software on data to ensure an event would be triggered

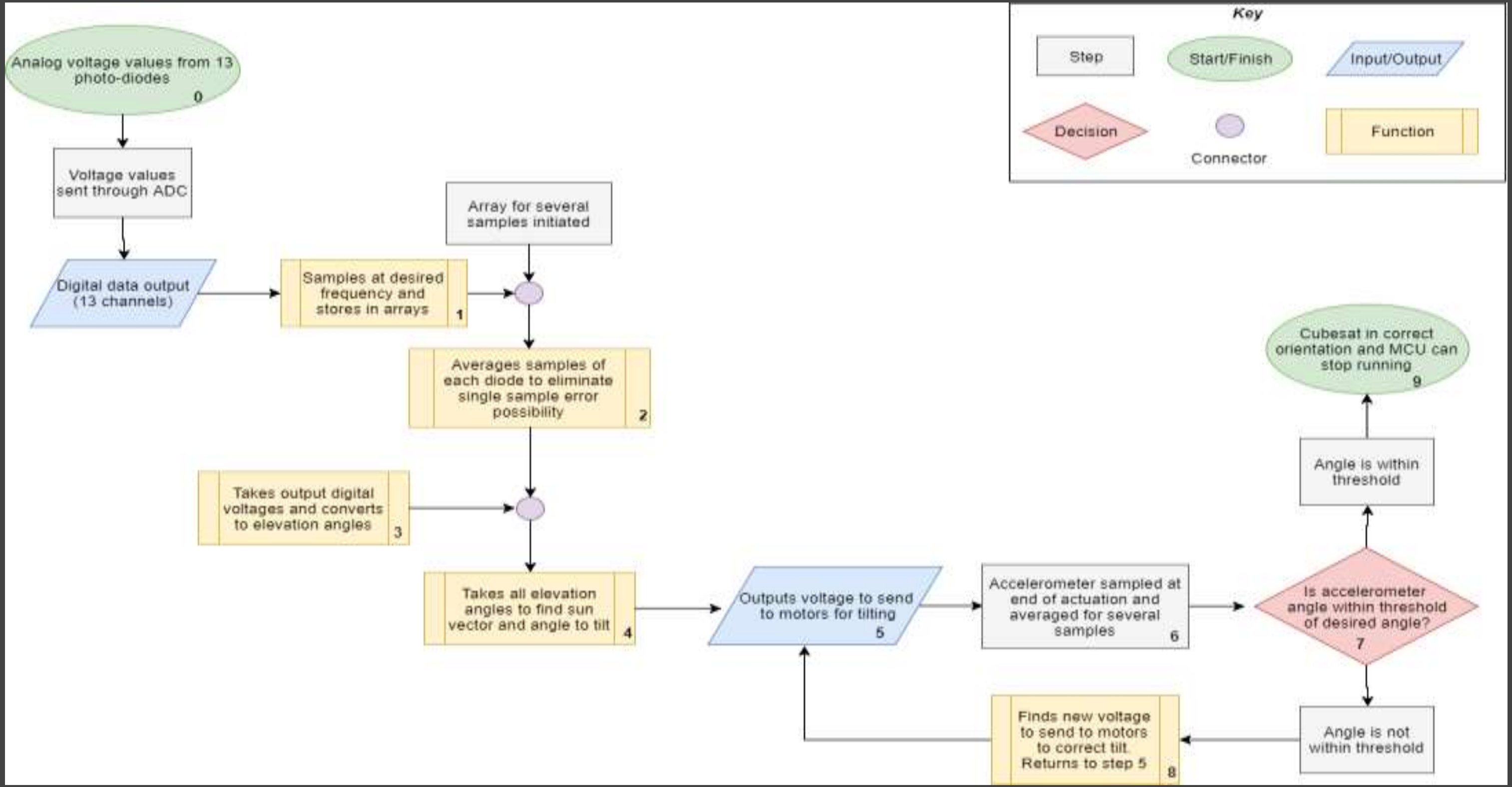


Instrument Testing (Post-Assembly)

5. Repeat steps 2 & 3 but with full instrument (both DTSs and DFR) active
6. Run post-processing analysis on manually recorded data
   - The average charge, mass, and velocity will be known from the pickup tube
   - Compare code output to knowns in order to validate post-processing code
7. Repeat until confident in trigger software and post-processing code
8. Move on to final testing procedure (see ConOps)

Software Backup Slides

ARS Software Flow Diagram



Instrument - Post Processing Software

Specific Requirement

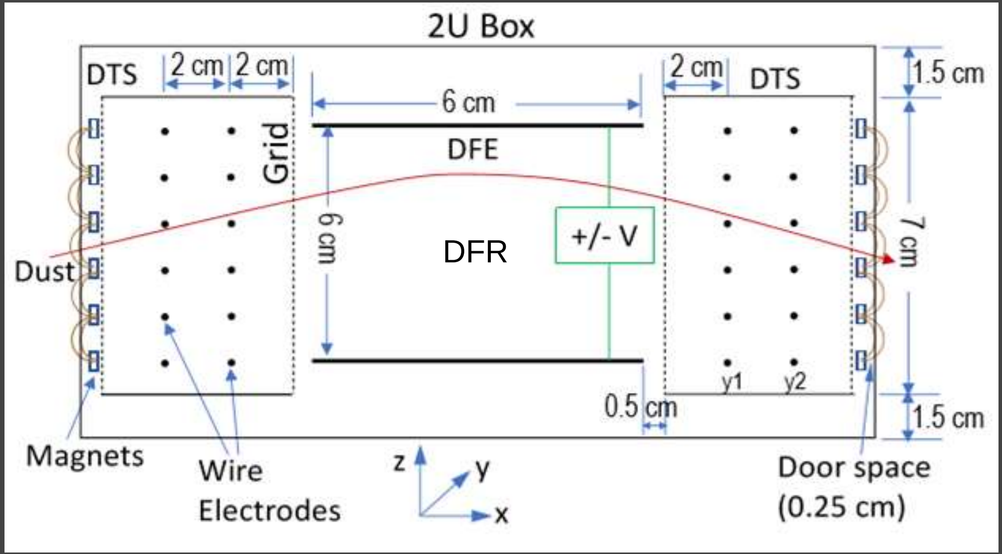
6.1 - The post-processing software shall extract mass, charge and velocity information from the dust data.

Why?

Overall goal of instrument is to determine these quantities for dust particles

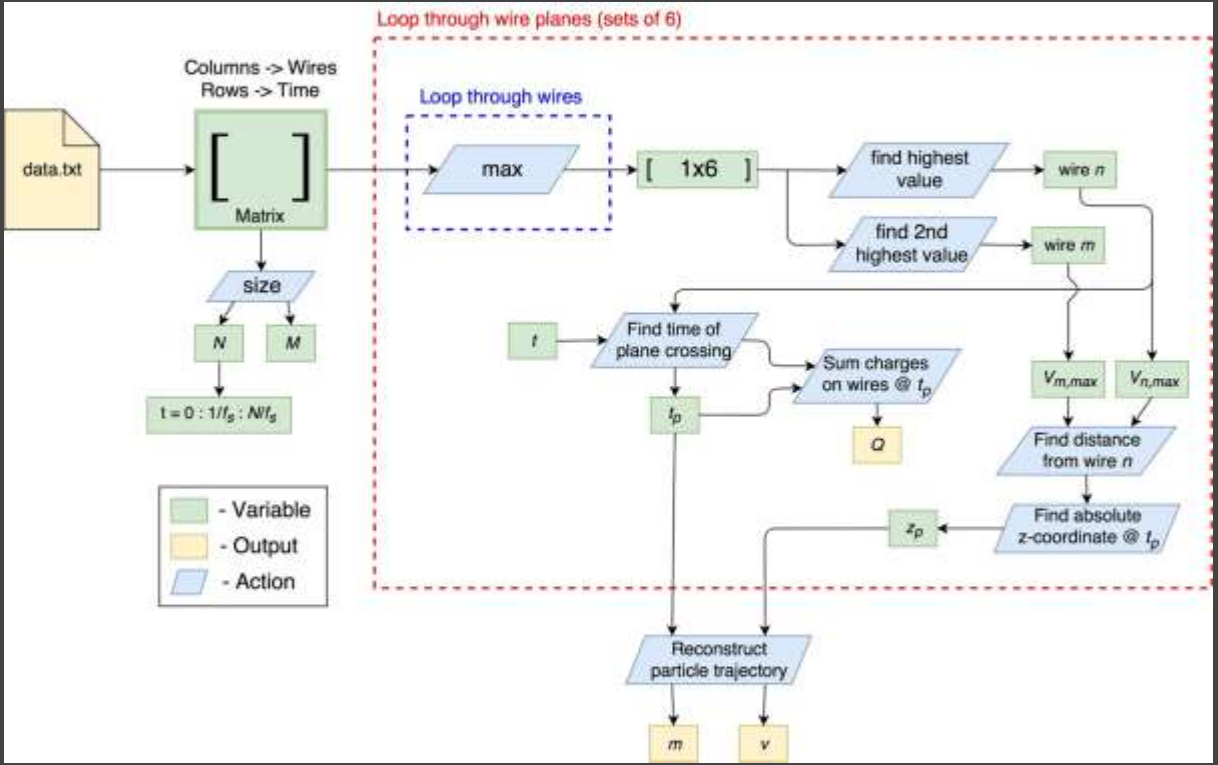
- Velocity from time between two DTS wire planes
- Charge from total accumulated charge on each 6 wires in 1 plane
- Mass from deflection angle through the DFR

Instrument – Post Processing Software



- Velocity from time between two DTS wire planes
- Charge from total accumulated voltage on each 6 wires in 1 plane
- Mass from deflection angle through the DFR

Post-Processing Flow Chart

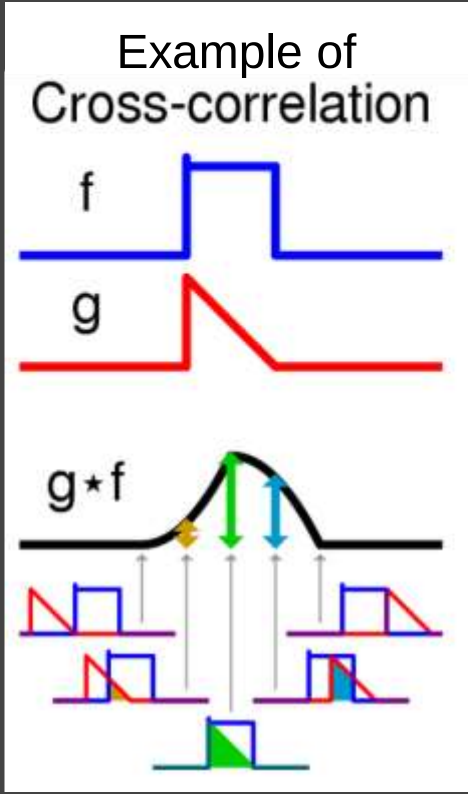


Requirement 6.1 Satisfied

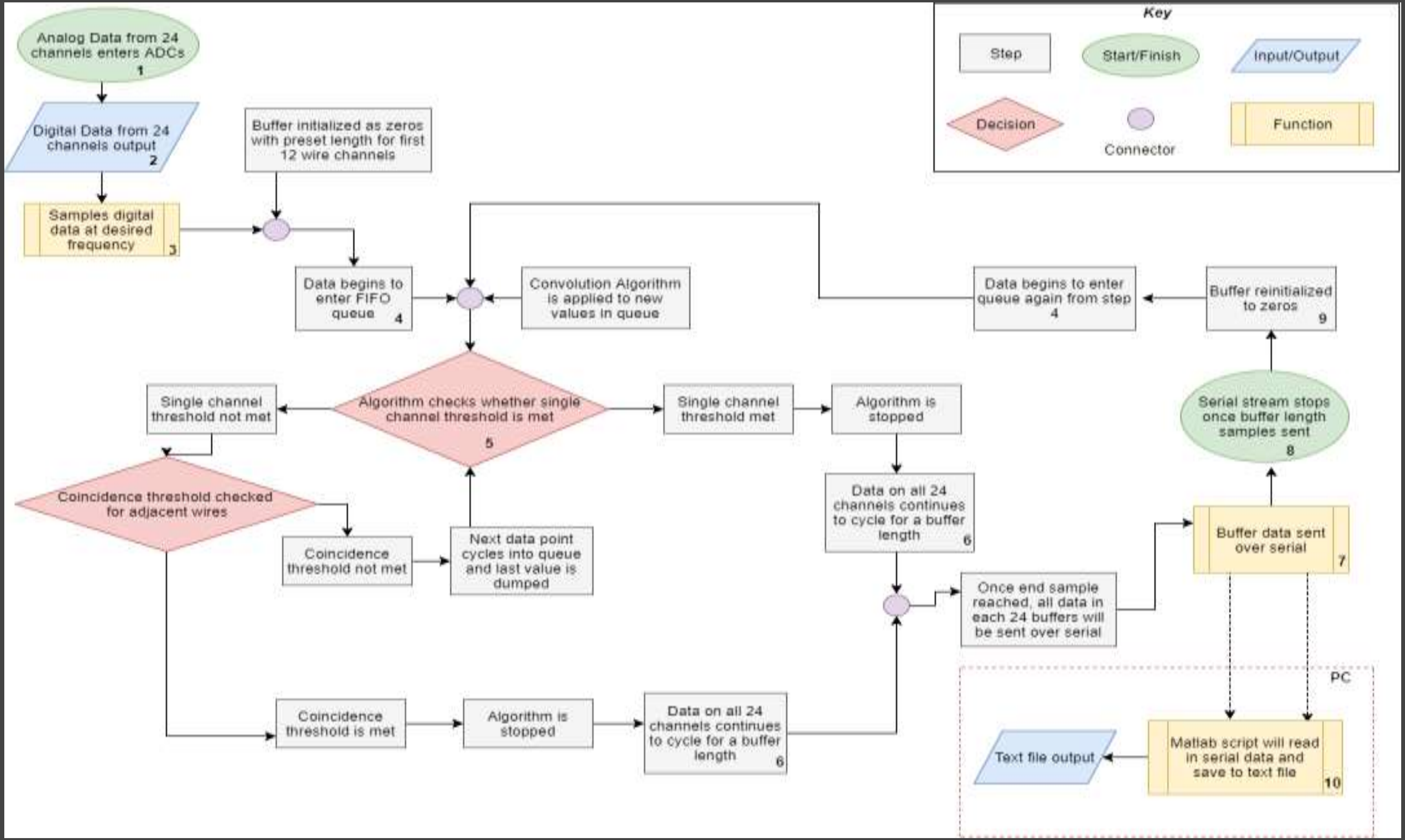
Trigger Method – Cross Correlation

- Cross correlation (sliding dot product) **measures overlap between two signals**
- Trigger software takes cross correlation to compare filter and data stream
- Dust event triggered when cross correlation value exceeds threshold
  - Threshold will be determined from calibration with multiple data sets

- Output of filter: $Y_0 = 2Y_{-1} - Y_{-2} + 2X_{-W/4} + 2X_{-3W/4} - X_{-W}$

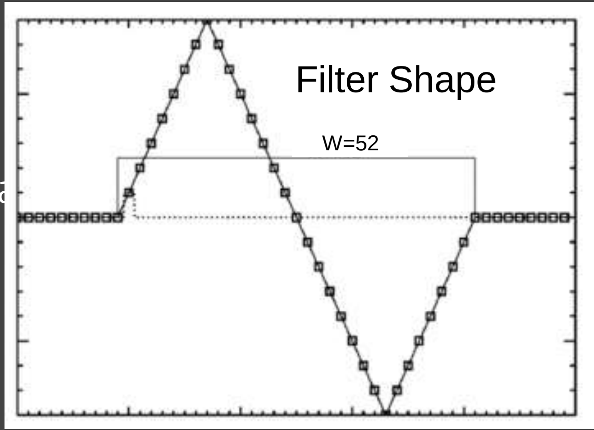


Instrument - Event Detection



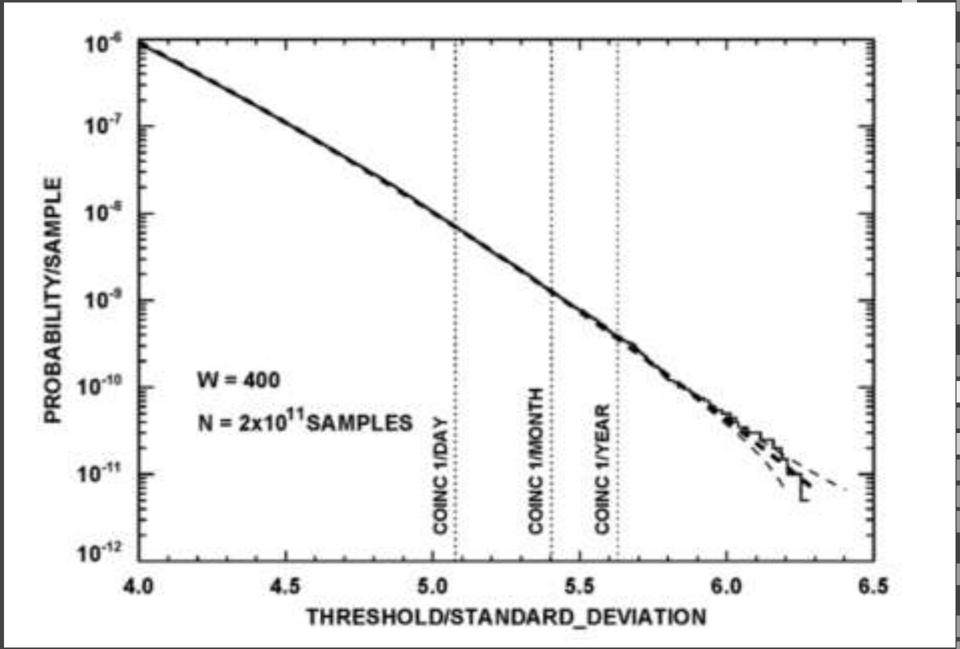
Filter Design

- 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 exceeds 3*noise

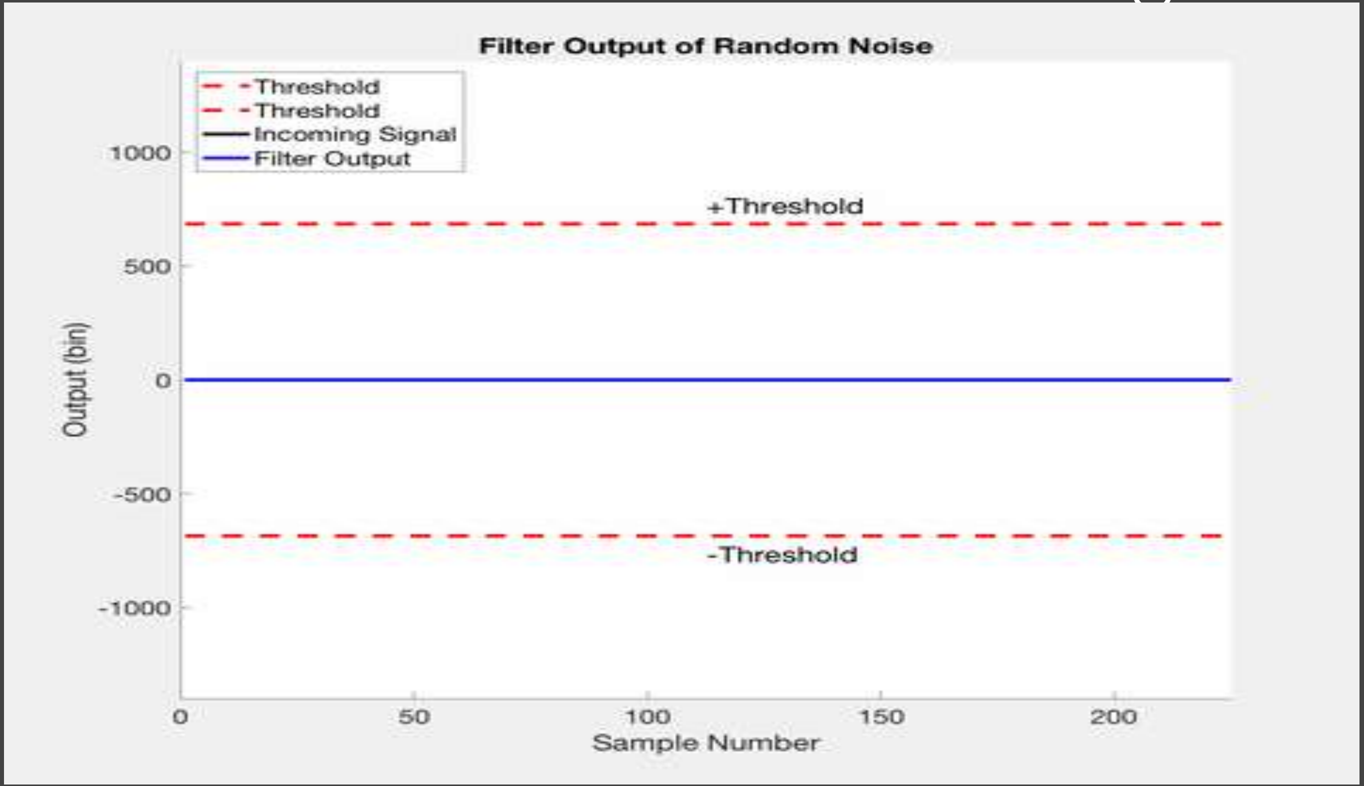


Trigger Rate

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

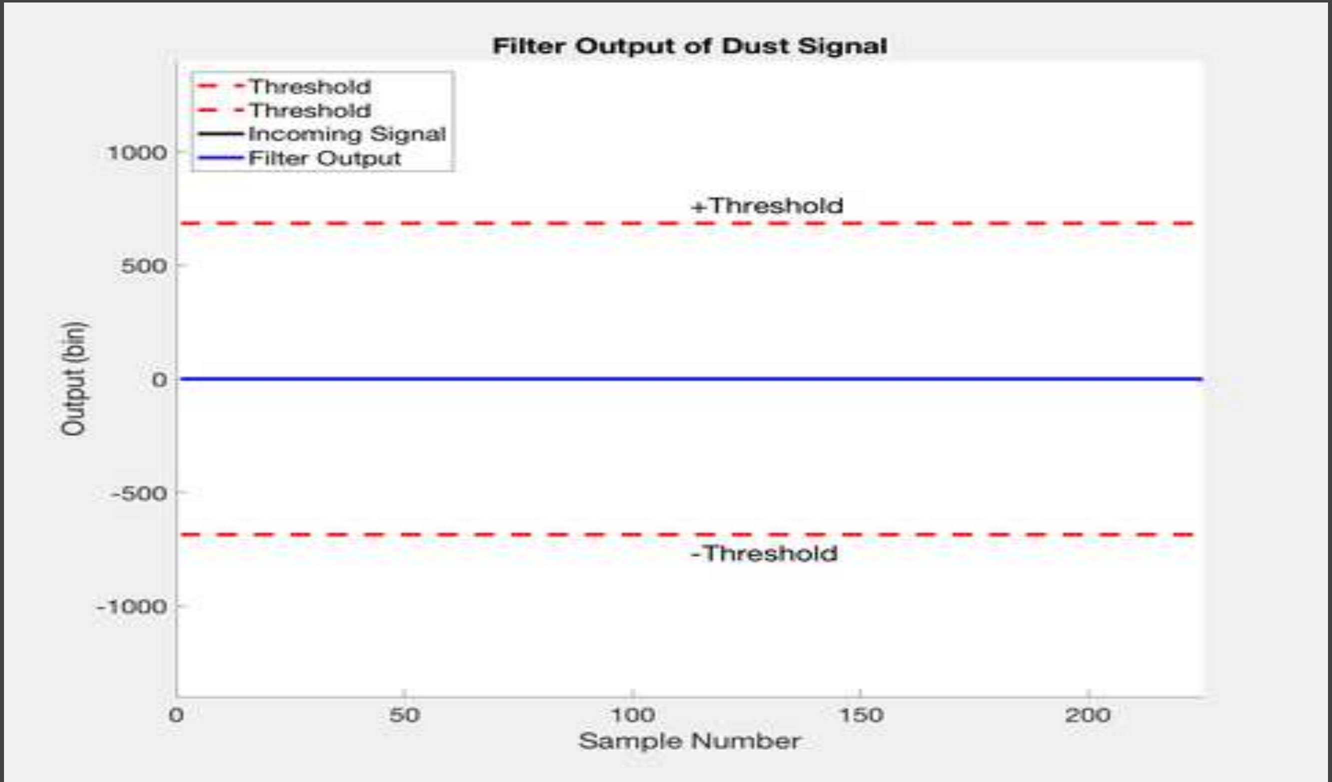


Instrument – Noise Filtering



Noise ignored with stable filter → Requirement 6.3.1 satisfied

Instrument – Event Detection



Event detected with stable filter → Requirement 6.3.2 partially satisfied

Trigger Software (Pre-Instrument)

Objective	Verify real time capabilities and trigger algorithms on microcontroller
Date	March 5th - March 18th
Location	ITLL
FR Verified	FR6: The software shall be capable of data processing, detecting dust events, and running ARS algorithms.

Data Needed	Sampling Rate
Previous Dust Data	Every millisecond

Equipment Needed	Procurement
STM32F4 Microcontroller	Built
Power Supply	Borrowed
Computer	Owned

- Run trigger algorithms on microcontroller and ensure microcontroller outputs data
- Ensure microcontroller can sample, convert, and run algorithms within 1 ms

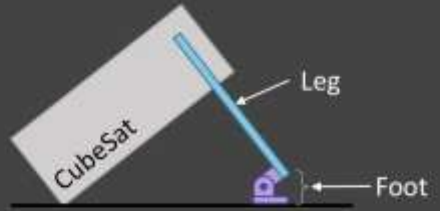
LASP Adamant FSW Framework

“Adamant is a component-based, model-driven framework designed for constructing reliable and reusable embedded, real-time software systems.” - Architecture Description Document

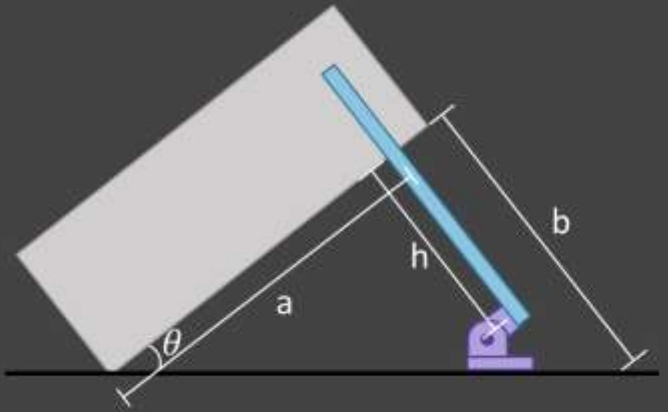
- Ada-based
- Integrated unit testing

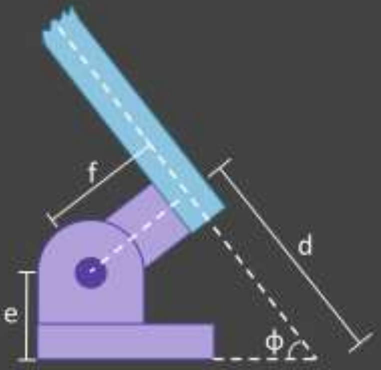
Mechanisms Backup Slides

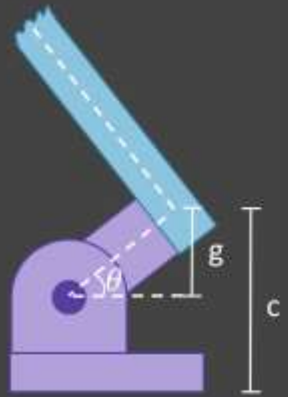
Scissor Lift Tilting Algorithm



$$b = a * tan(theta)$$







$$d = c * cos(theta)$$

$$g = f * sin(theta)$$

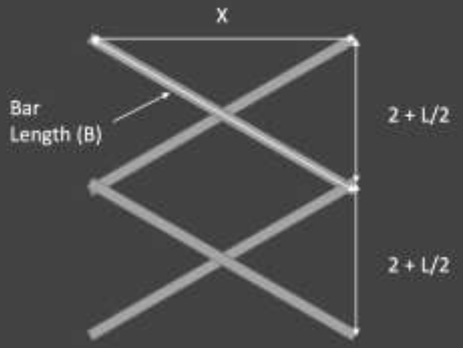
$$c = e + g$$

$$h = b - d$$

Scissor Lift Tilting Increment

- Can't solve for the tilt angle from leg length
  - Iteratively solve for leg length based on tilt angle
  - Compare leg length to closest possible from model to the right.
  - At all times, leg length error is < 10 μm
    - Error in angle is <38.4 mas

Then Need To Determine Horizontal Actuation



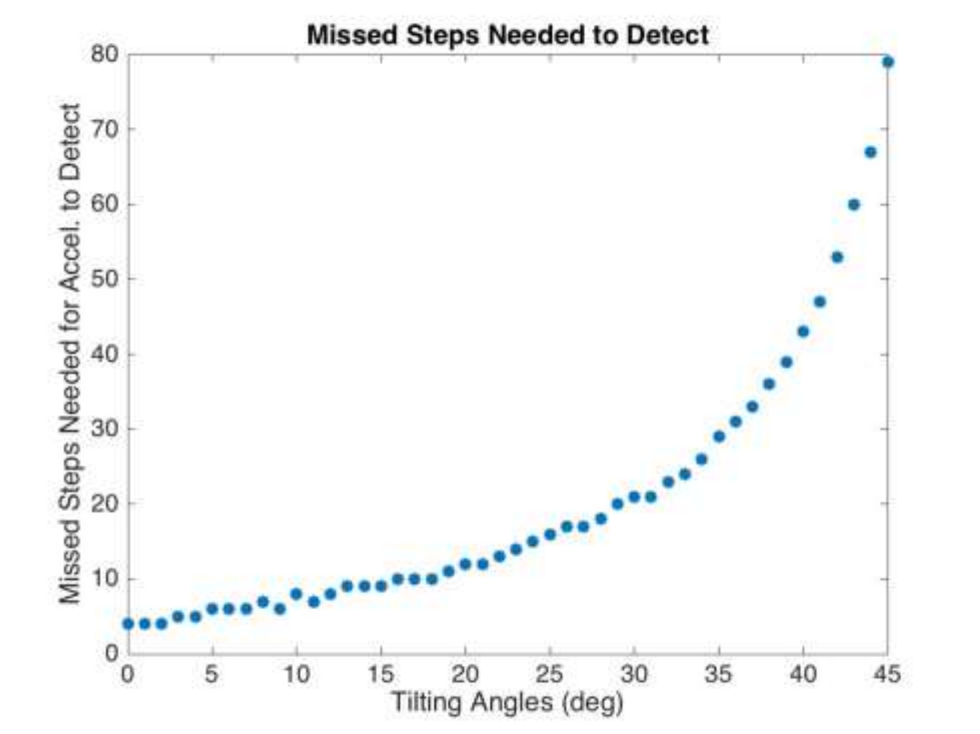
$$X = \sqrt{B^2 - (2)^2}$$

$$X' = \sqrt{B^2 - \left(2 + \frac{L}{2}\right)^2}$$

Horizontal Actuation $= \Delta X = X - X'$

Missed Steps Analysis

- Tilting Angle is not a linear function.
- Missed steps needed for accelerometer to detect is variable.
  - In all cases, missed steps needed > 5



Locking Mechanism Trade Study

	Weight	Solenoid	Worm Gear	Lead Screw
Size	0.3	3	1	5
Holding Force	0.3	4	5	2
Mass	0.1	4	1	5
Cost	0.1	4	1	5
Integration	0.2	2	5	4
Total		3.3	3	3.9

Locking Requirement Satisfaction

Specific Requirements:

4.123: The actuators shall lock when they reach the desired angle to maintain the tilt within 1 degree.

Why?

Need the legs mechanism to lock after tilting so that we can stop supplying power to the motor.

Satisfaction:

Based on solidworks analysis, maximum torque on motor is 0.1626. Detent torque of motor is 1.5 Nm.

1.5 Nm > 0.1626 Nm
Will be able to lock without power

→ Requirement 4.123 satisfied

Mechanisms Mass and Size Requirements

Specific Requirements:
The ARS shall take up less than 3U of the CubeSat model's interior.
Why?
Need to leave mass and and volume for other systems that are outside of the scope of the project.

Mechanisms Mass and Size Requirements

Satisfaction:

- Mass: Solidworks model
- Volume: Assumed Rectangular Components

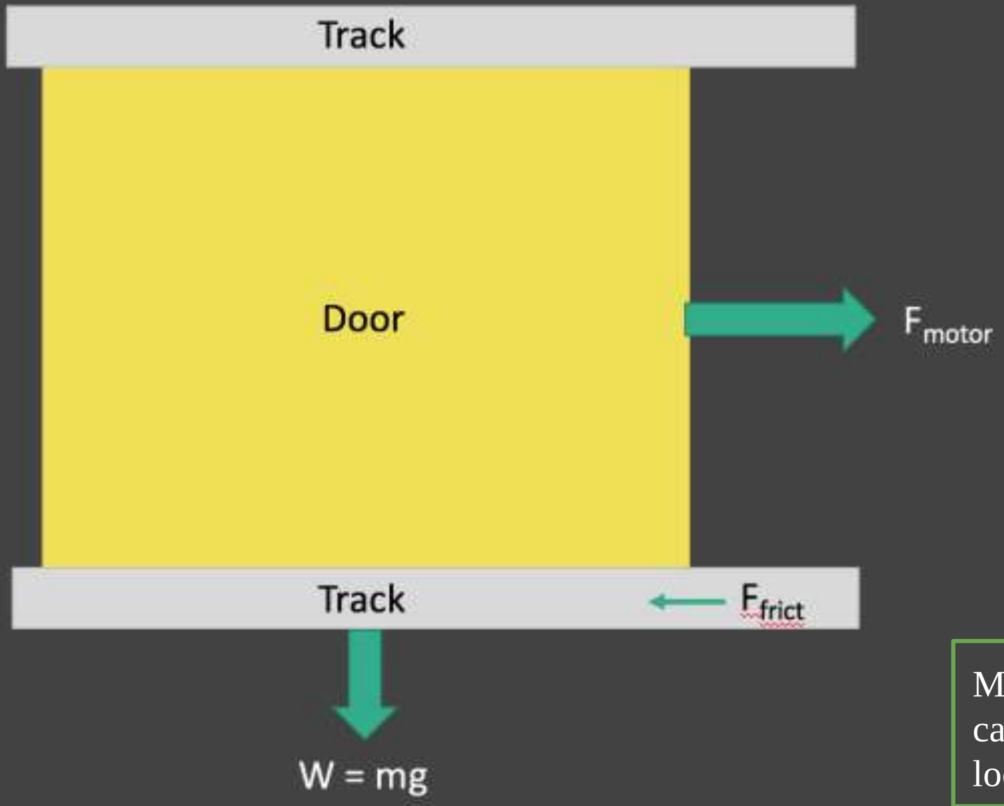
Component	Mass	Volume
Scissor Lift System	1.239 kg	1253.9 cm^3
Sliding Door System	0.504 kg	353.1 cm^3
Total	1.743 kg	1606 cm^3

1606 cm^3 < 3000 cm^3
Fulfills 3U volume requirement

1.743 kg < 6 kg
Fulfills 3U mass requirement

Requirement 4.123 satisfied

Locking Analysis – Doors



μ = 1.5 for Al on Al
m = 0.05832 kg
g = 9.81 m/s^2

$$F_{frict} = N\mu \qquad N = mg$$

$$F_{frict} = (0.05832)(9.81)(1.5)$$
$$F_{frict} = 0.803N$$

Motor can provide 10.2 N of force, so can overcome friction that might cause locking

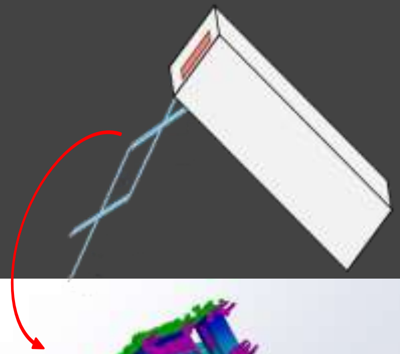
Locking and Deflection Analysis – Tilt

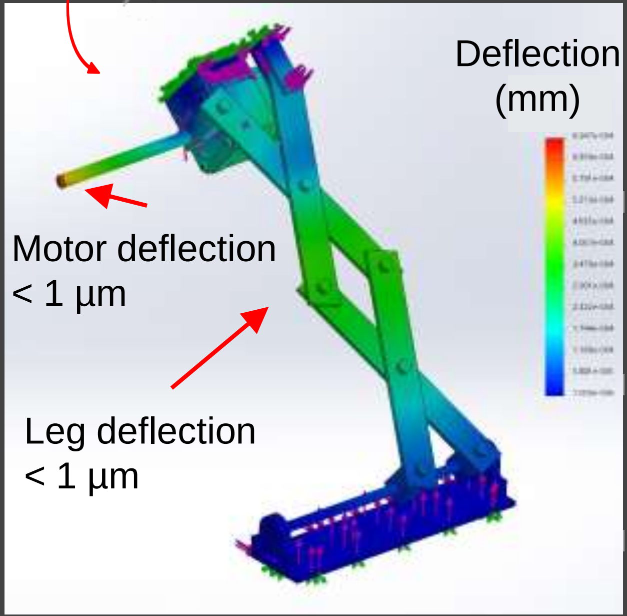
Must tilt the adjusted mass of the Cubesat.

- Concern with deflection and stress caused by loading
- Fully Deployed (largest forces)

Solidworks static analysis

- Torque put back on the motor is 0.045 Nm
- Torque from weight is 0.1176 Nm
- Motor can supply 0.26 Nm





Max torque (0.045+0.1176) < 0.26 Nm
No locking up

Requirement 4.1.2 satisfied

Locking and Deflection Analysis – Tilt

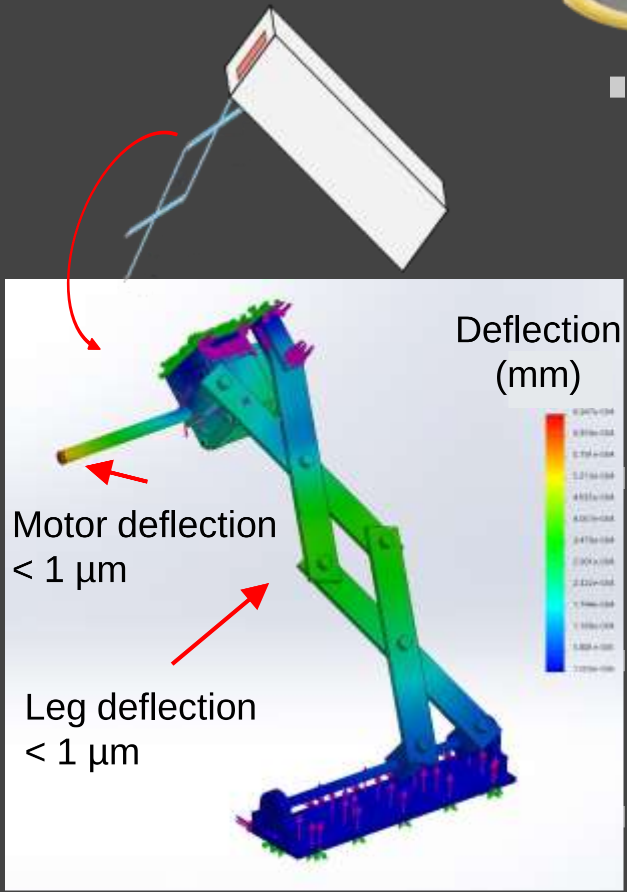
Solidworks static analysis: Fully extended (largest forces)

- Minimal deflection
- Total counter-torque: 0.16 Nm
- Motor can supply 0.26 Nm

Counter-torque < 0.26 Nm
No locking up

↓

Requirement 4.1.2 satisfied

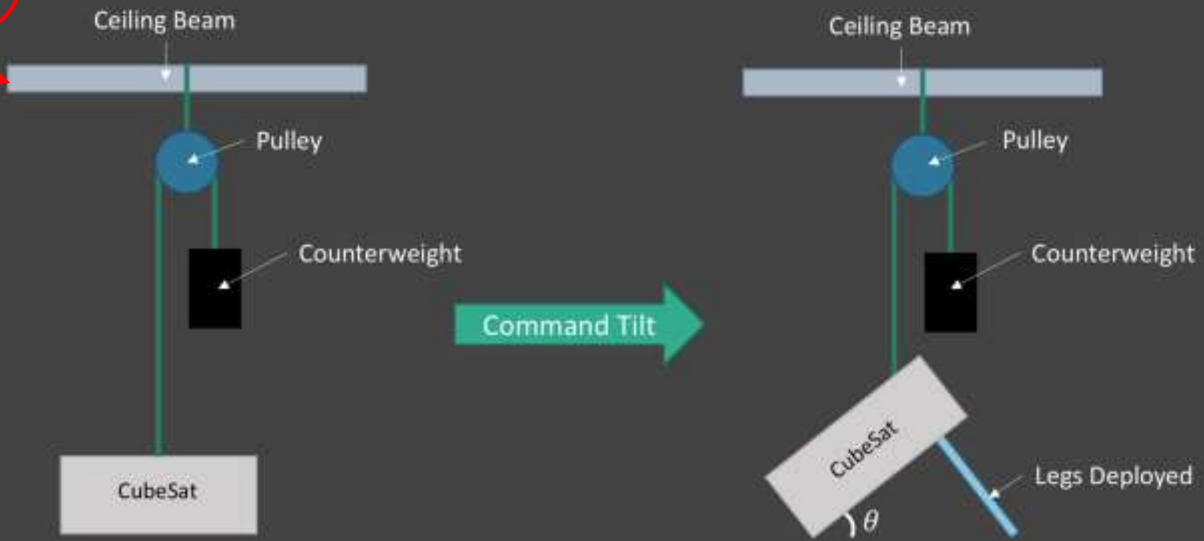


Door Verification and Validation

Door: Inspection/Demonstration

- Apply voltage to drivers and verify motor turns
- Integrate door and motors. Apply voltage to drivers and verify the door moves
- Press button, verify that it cuts power to the motor
- Integrate door and motor with button. Move the door with the motor and ensure it has enough force to push the button. Verify power is cut to the motor.

Tilting Mechanism Testing

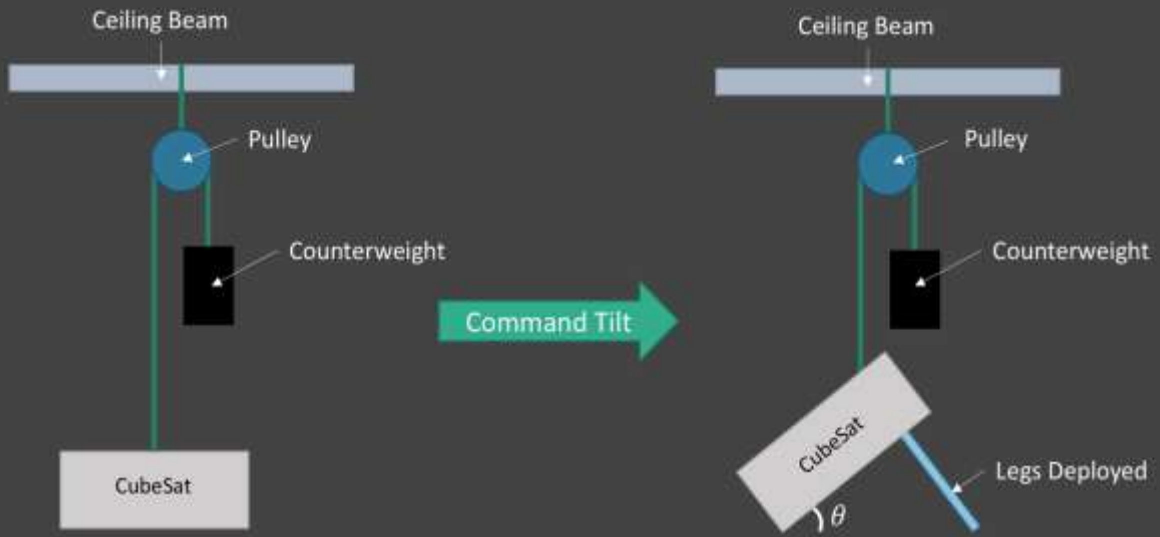


Tilting Mechanism Test

Objective	Compare measured tilt angle to commanded angle as well as the expected angle from the matlab model. Verify that measured angle is within ±0.5° using the accelerometer.
Location	Senior Projects Depot
FR Verified	FR5: CubeSat tilts 45° or optimal amount ±0.5°

Data Needed	Resolution
Measured Tilt Angle	0.5°
Modeled Tilt Angle	8 mas
Commanded Tilt Angle	Exact

Equipment Needed	Procurement
Tilting Mechanism	Built
Power Supply	Borrowed
Computer	Owned
Pulley, Cord, Weight	Buy or Borrow



Electronics Backup Slides

Instrument Digital System

Specific Requirements:
5.2.1 - The hardware shall convert analog signals from each of 24 instrument amplifiers to digital at 1 kHz.

Why?
Customer specified 10 samples per waveform are needed for a 2 m/s particle which creates a 10 ms signal

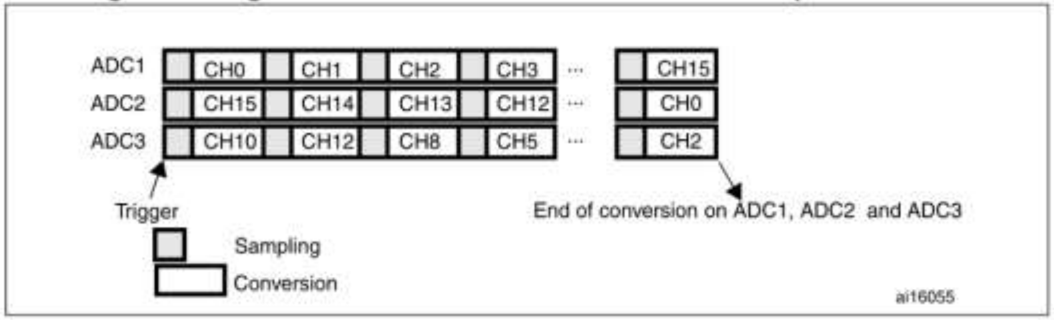
Designs Driven:
- Custom instrument embedded system including microcontroller with internal ADCs and custom analog pin protection

Instrument - ADC Sampling

STM32F427 Microcontroller

- Three ADCs with 24 channels
- 1 kHz timer interrupt triggers channel conversion sequence

Figure 55. Regular simultaneous mode on 16 channels: triple ADC mode

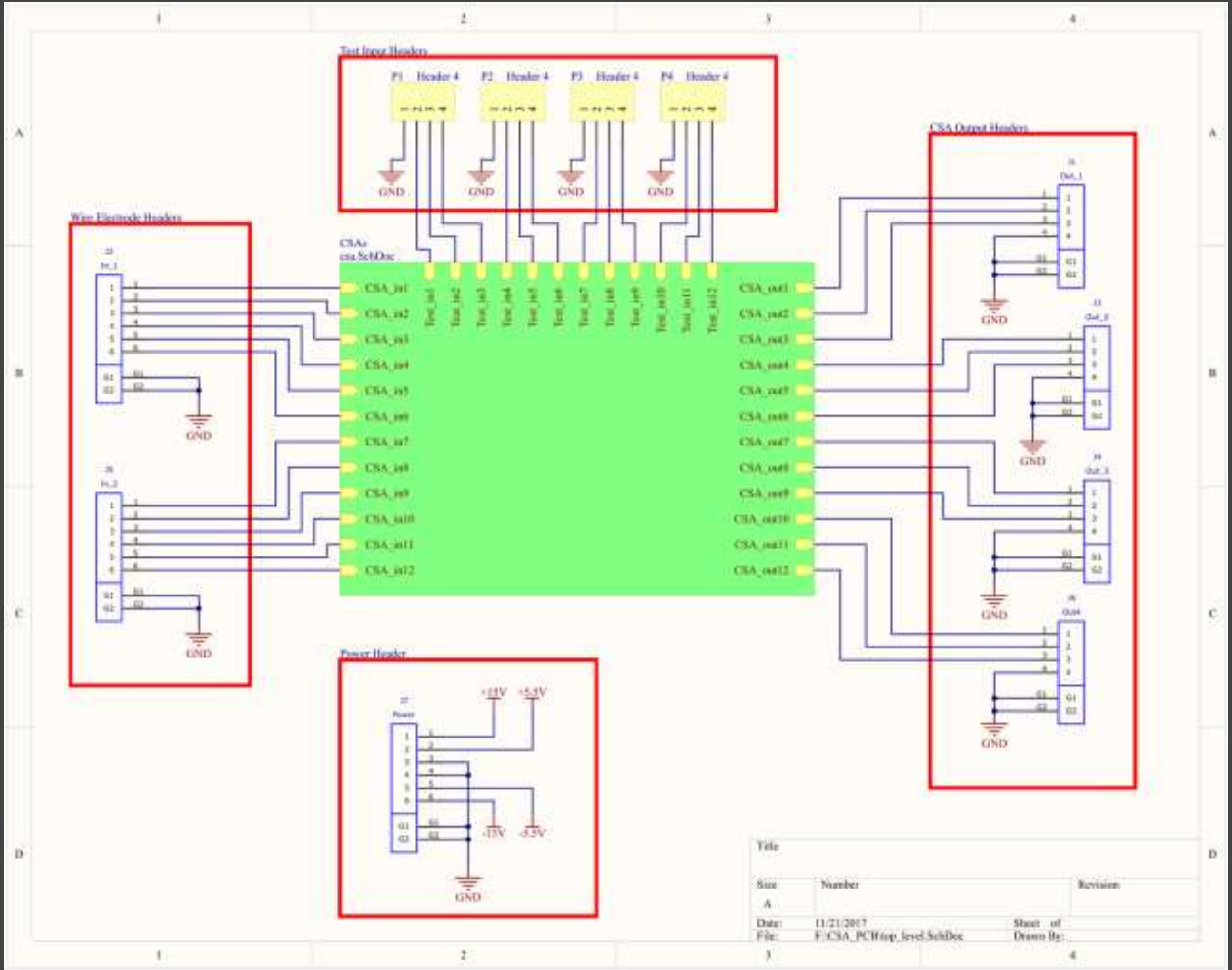


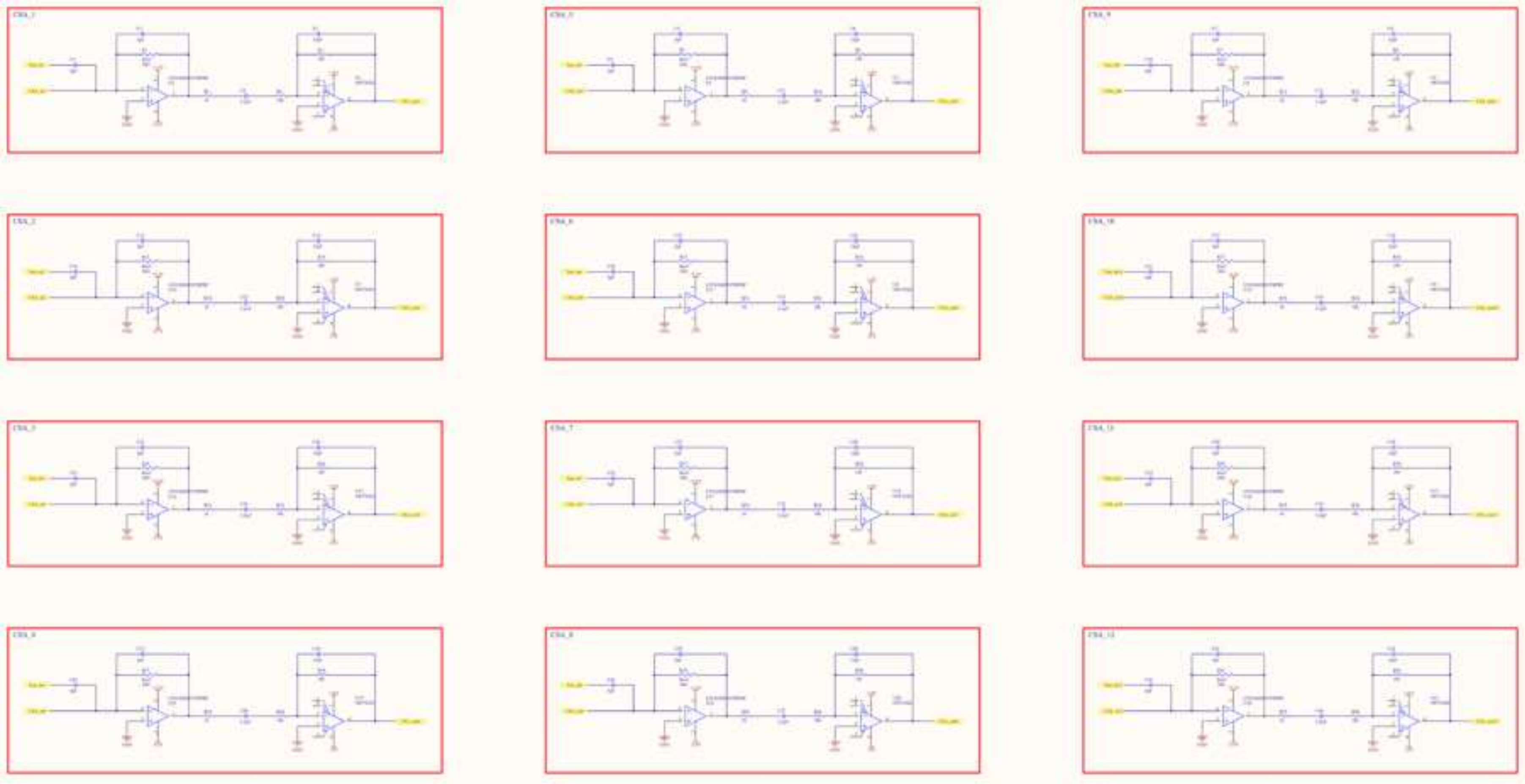
$$f_{ADC,max} = 30\text{ MHz} \Rightarrow t_{cycle,ADC} \cong 33\text{ ns}$$
$$t_{sample} = 3\text{ cycles}$$
$$t_{conversion} = 12\text{ cycles}$$
$$\therefore t_{channel} = 15\text{ cycles}$$

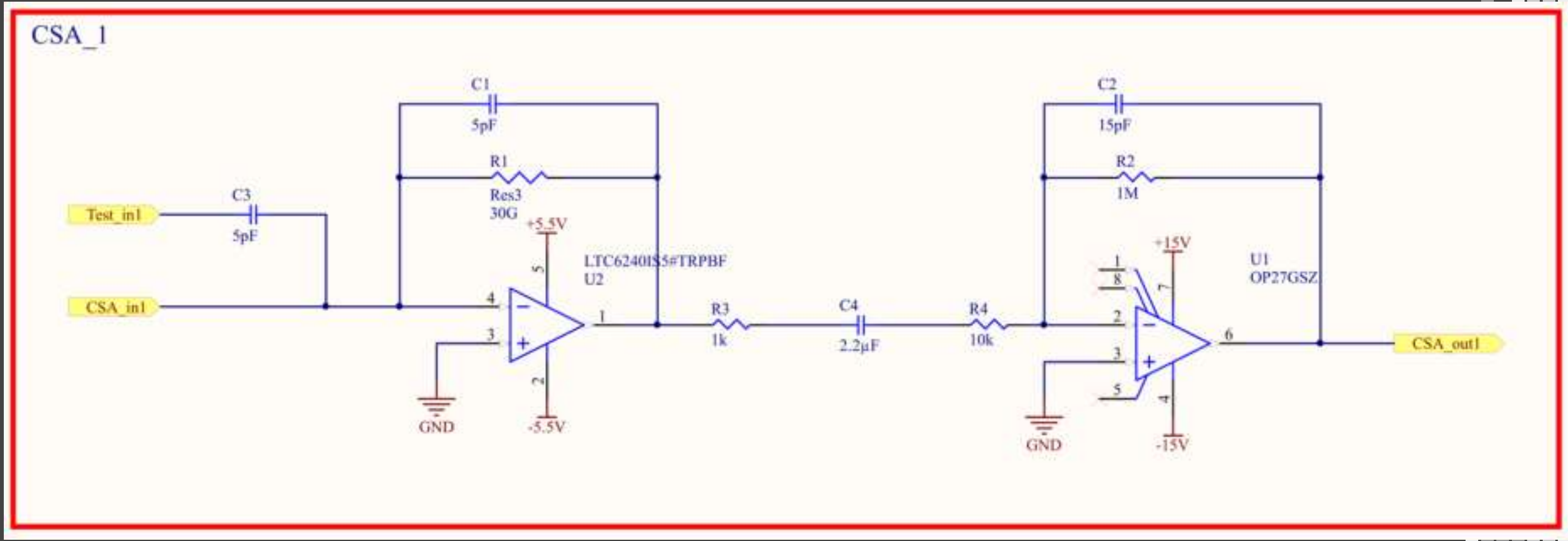
$$t_{24\ channels} = 15\text{ cycles} * 33\text{ ns/cycle} * 24\text{ channels}$$
$$\therefore t_{24\ channels} = 12\ \mu\text{s}$$

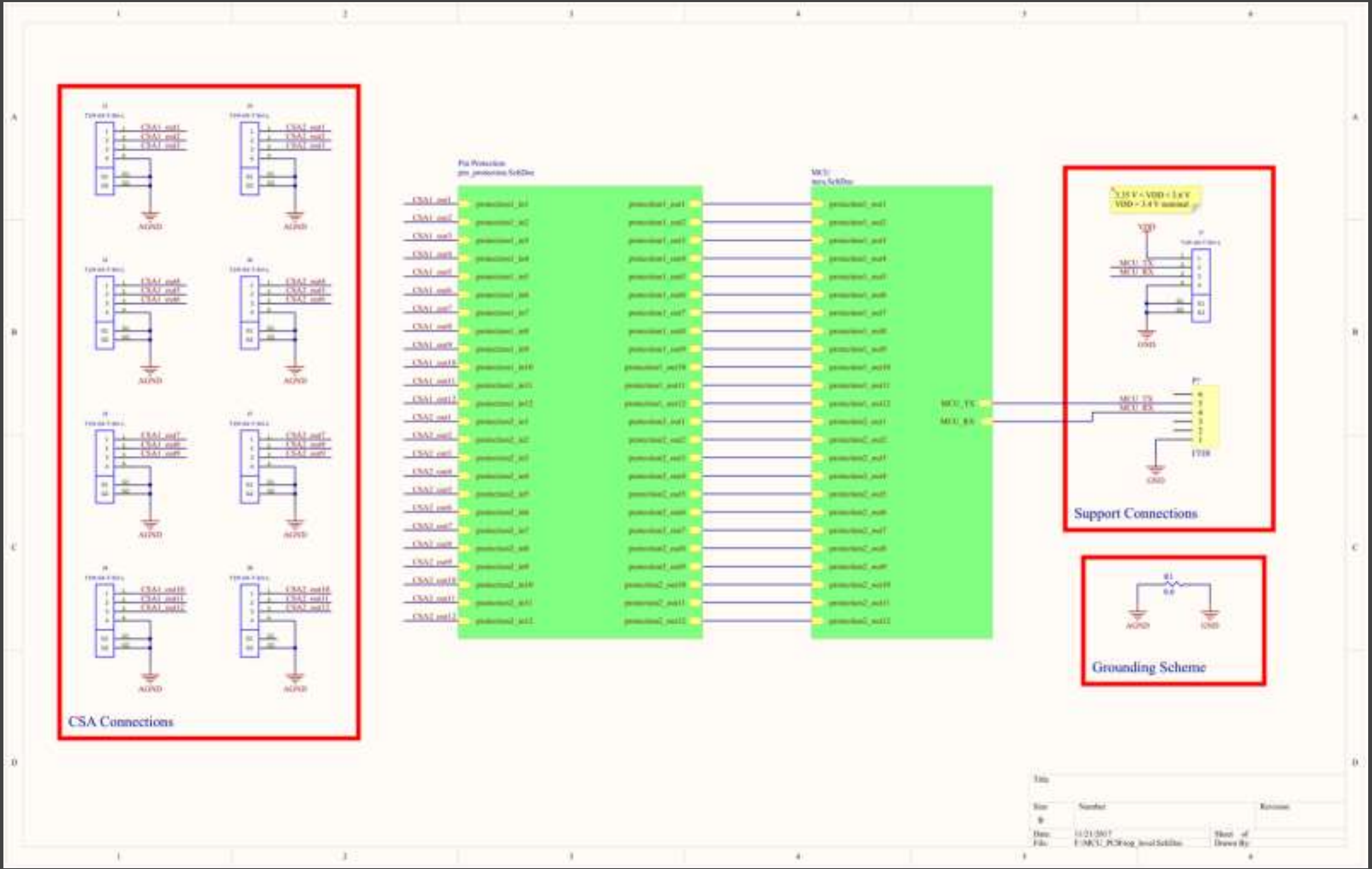
12 µs << 1 ms for 1 kHz sampling

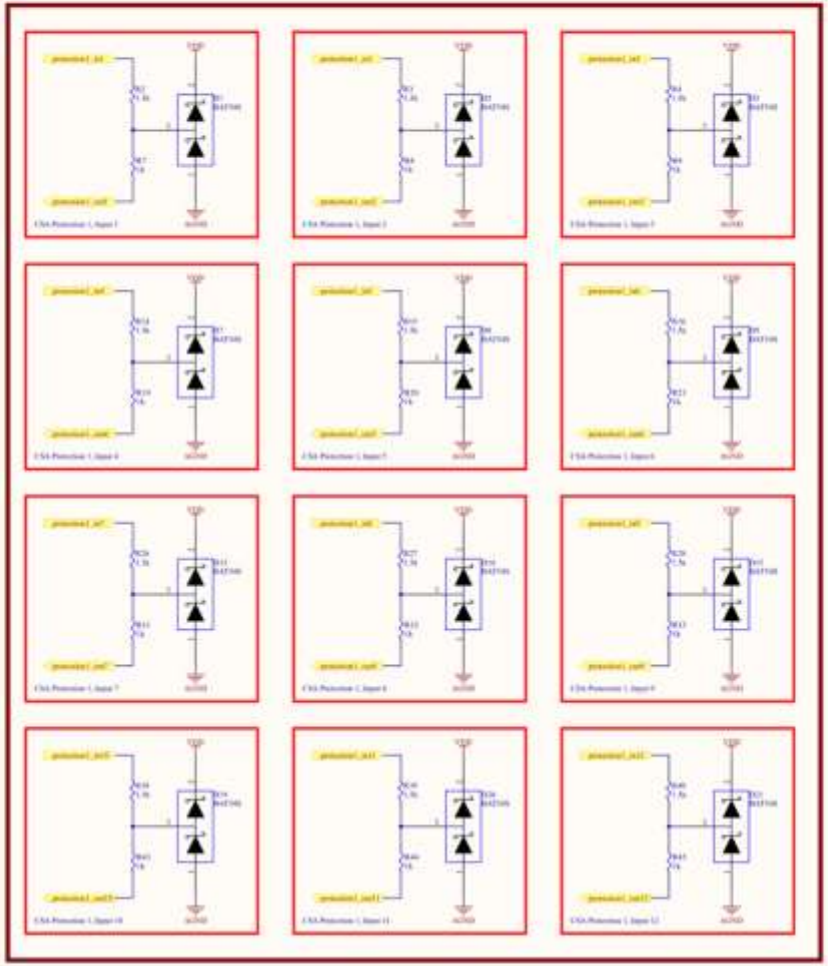
Requirement 5.2.1 satisfied


Test Input Headers
P1 Header 4
P2 Header 4
P3 Header 4
P4 Header 4
GND
Wire Electrode Headers
CSA Output Headers
CSAs
csa.SchDoc
CSA_in1
CSA_in2
CSA_in3
CSA_in4
CSA_in5
CSA_in6
CSA_in7
CSA_in8
CSA_in9
CSA_in10
CSA_in11
CSA_in12
CSA_out1
CSA_out2
CSA_out3
CSA_out4
CSA_out5
CSA_out6
CSA_out7
CSA_out8
CSA_out9
CSA_out10
CSA_out11
CSA_out12
Power Header
+15V
+5.5V
-15V
-5.5V
Title
Size
Number
Revision
Date:
Sheet of
File:
Drawn By:

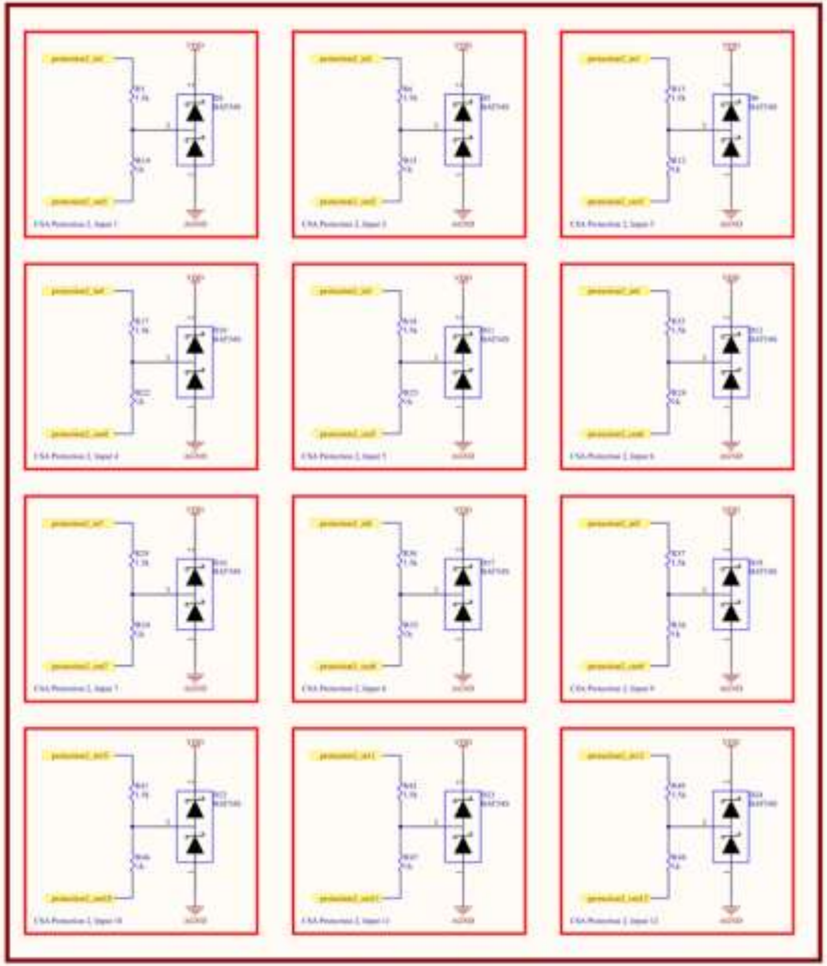



CSA_1
C1
5pF
R1
Res3
30G
C3
5pF
Test_in1
CSA_in1
+5.5V
-5.5V
GND
LTC6240IS5#TRPBF
U2
R3
1k
C4
2.2µF
R4
10k
C2
15pF
R2
1M
+15V
-15V
U1
OP27GSZ
GND
CSA_out1

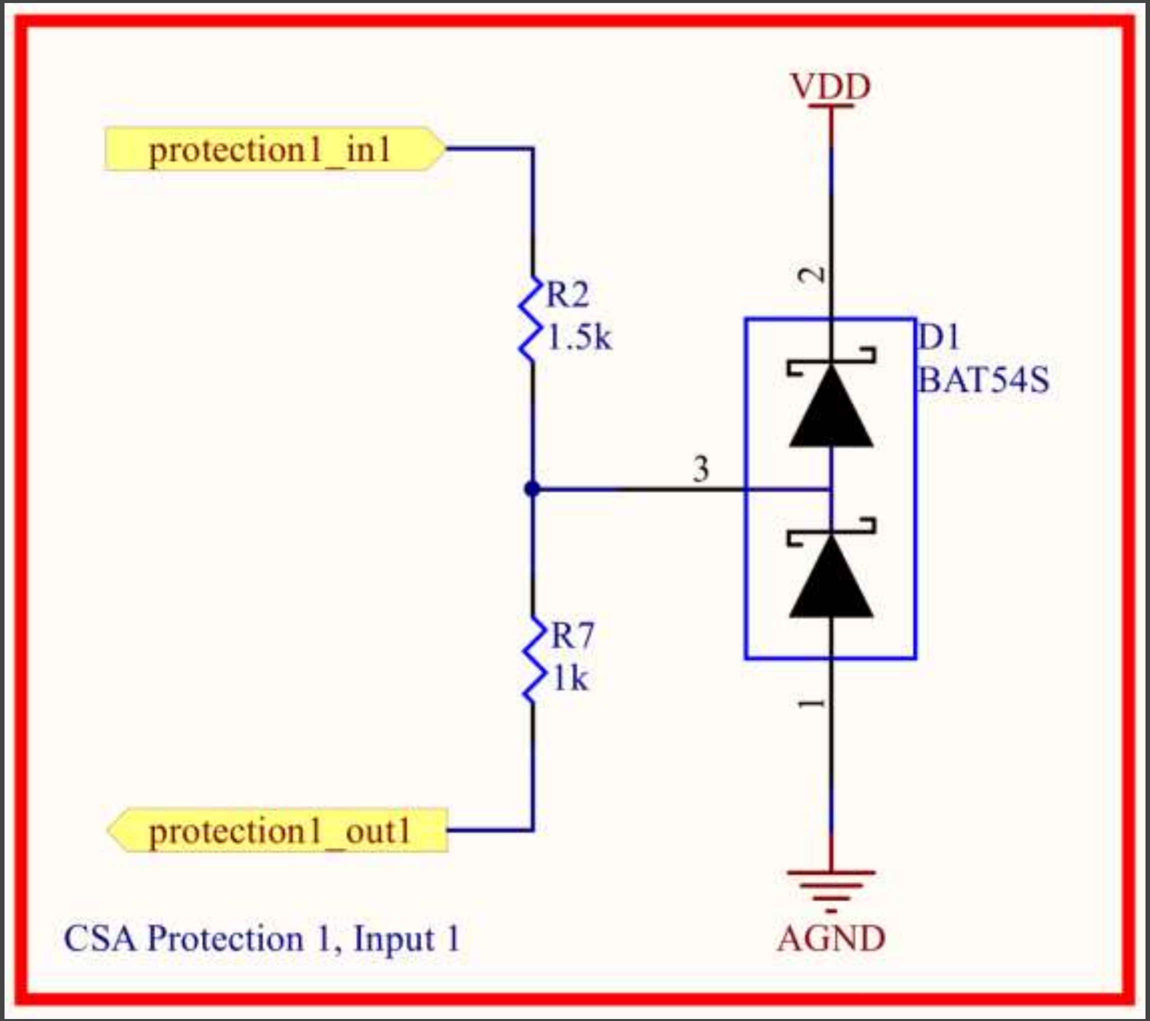

CSA Connections
Support Connections
Grounding Scheme
AGND
GND
VDD
MCU_TX
MCU_RX



CSA Group 1 Protection

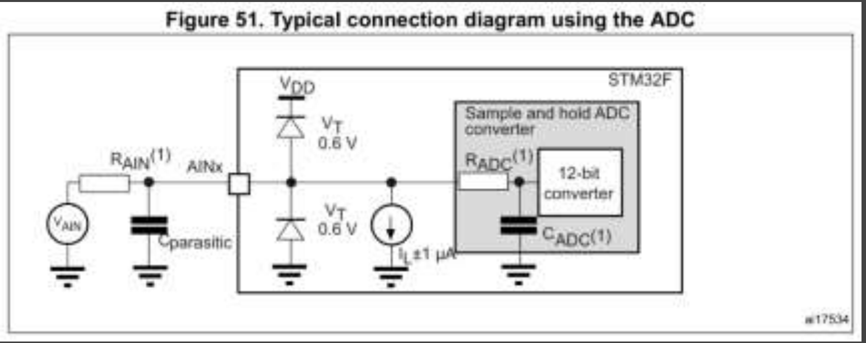


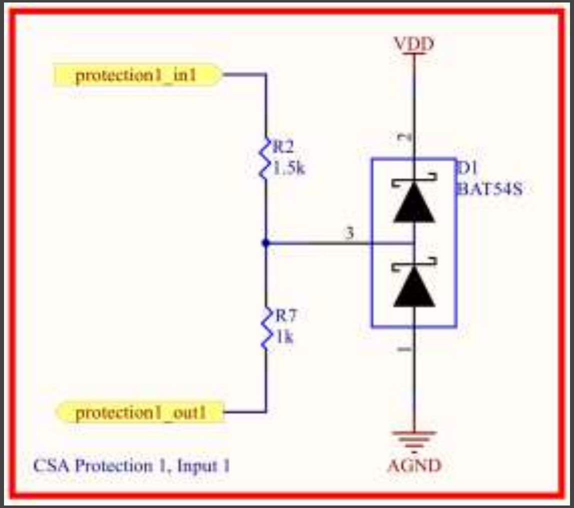
CSA Group 2 Protection



VDD
protection1_in1
R2
1.5k
2
D1
BAT54S
3
R7
1k
1
protection1_out1
CSA Protection 1, Input 1
AGND

Pin Protection





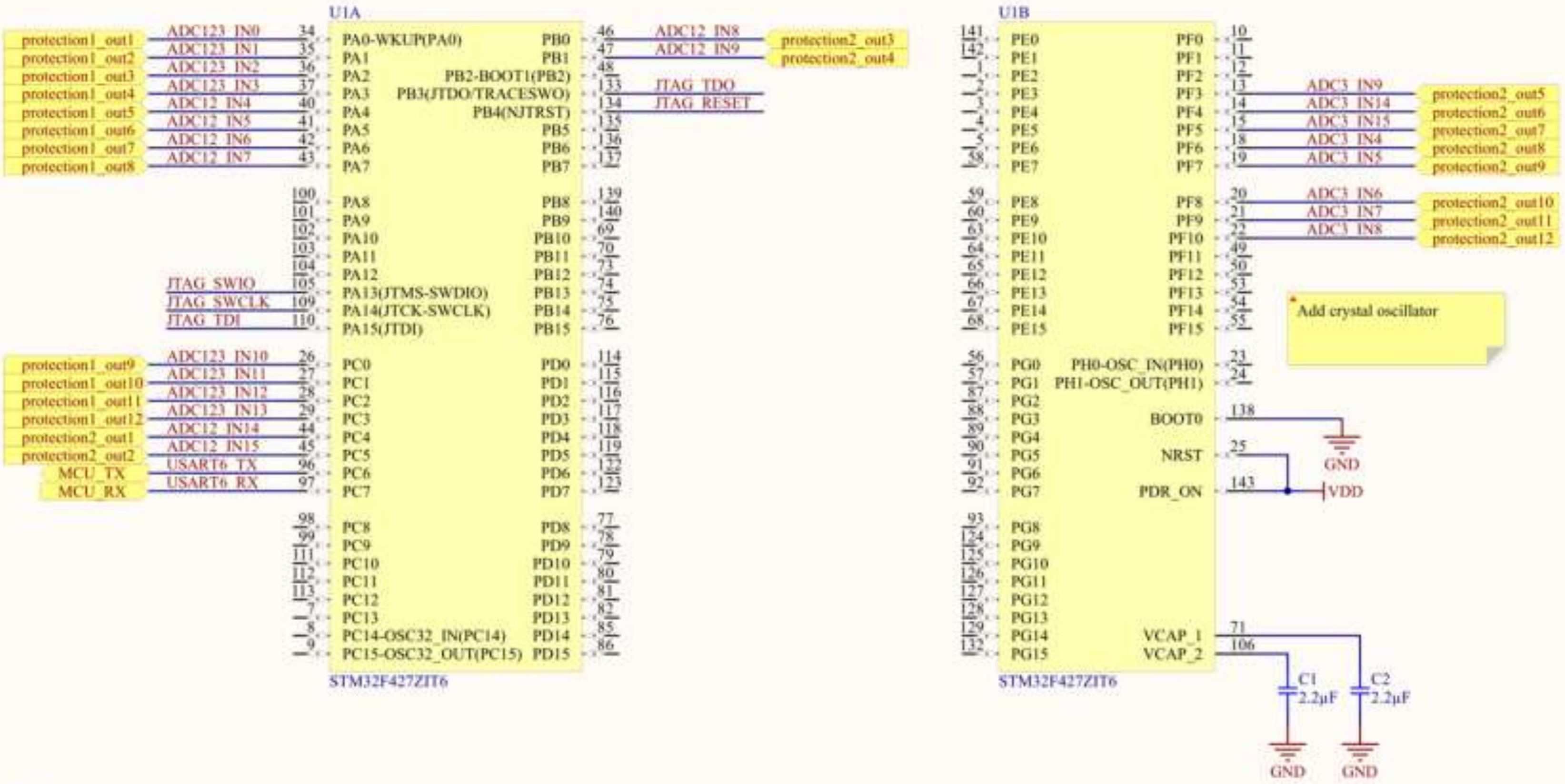
Clamping circuit to maintain 0 V < ADC_in < 3.3 V

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

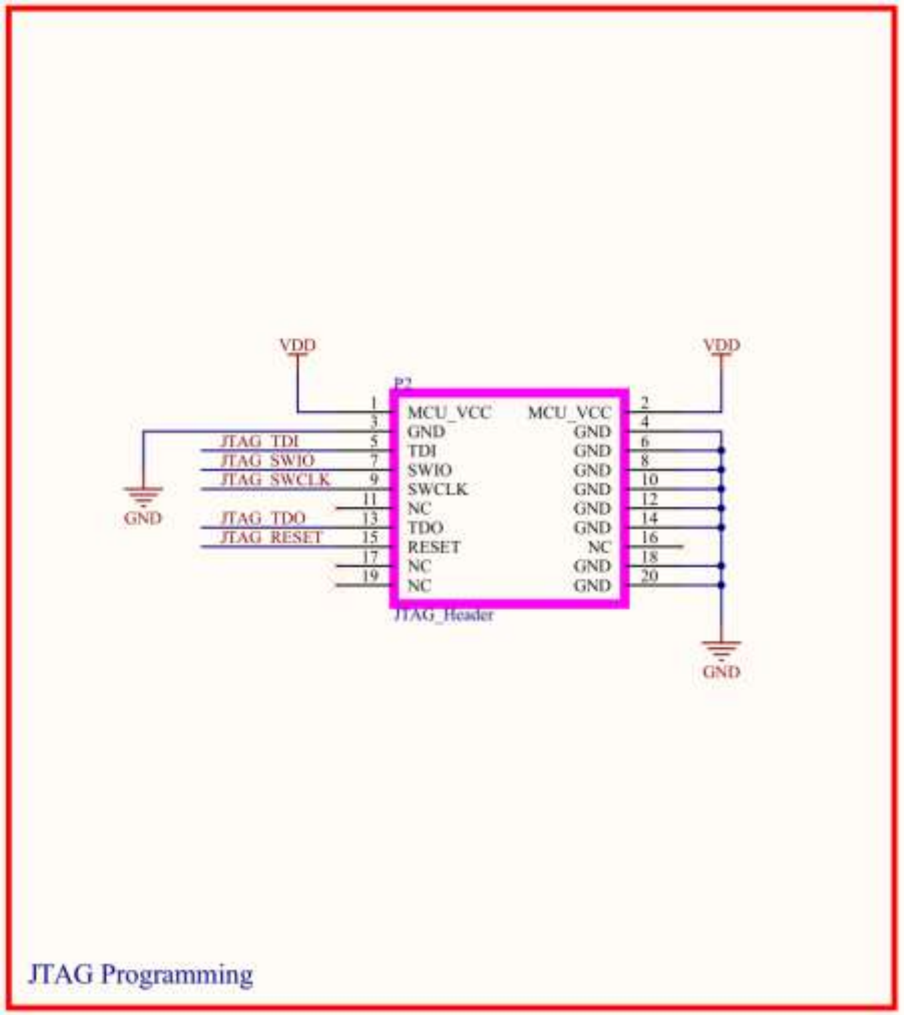
Need $V_{Shottky} < V_T$ = 0.6 V so that the MCU diodes don't burn out

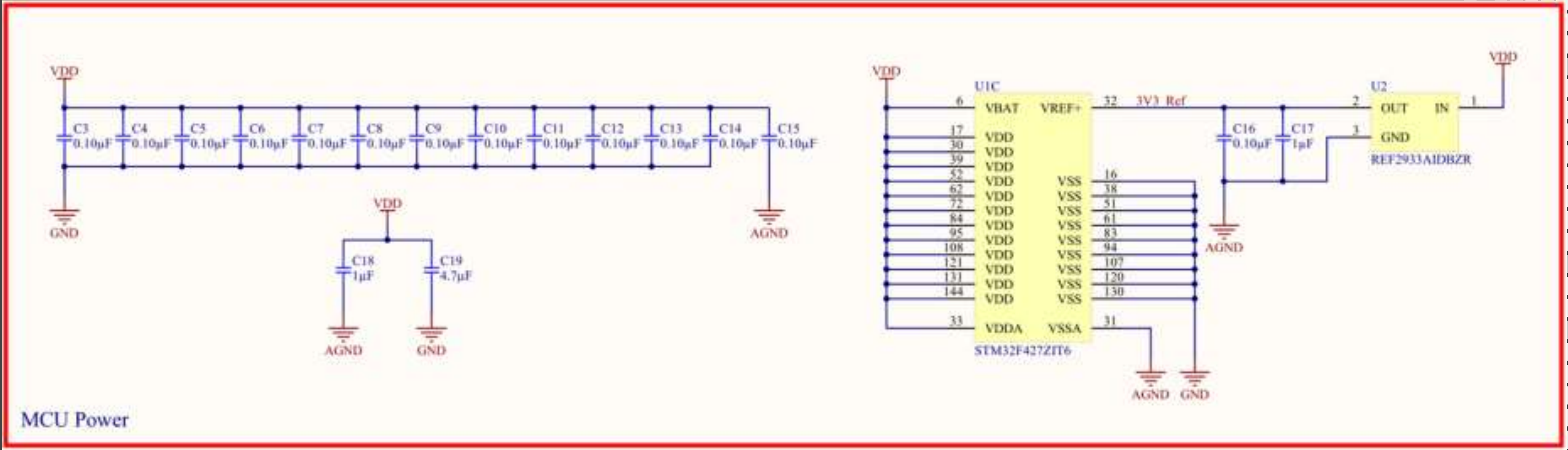
Maximum voltage difference is -15 V to GND. At 15 V, I_{R2} = 10 mA ⇒ $V_{Shottky}$ = 0.4 V

$V_{Shottky}$ = 0.4 V < 0.6 V = V_T ∴ acceptable pin protection


U1A
protection1_out1
protection1_out2
protection1_out3
protection1_out4
protection1_out5
protection1_out6
protection1_out7
protection1_out8
ADC123_IN0
ADC123_IN1
ADC123_IN2
ADC123_IN3
ADC12_IN4
ADC12_IN5
ADC12_IN6
ADC12_IN7
PA0-WKUP(PA0)
PA1
PA2
PA3
PA4
PA5
PA6
PA7
PB0
PB1
PB2-BOOT1(PB2)
PB3(JTDO/TRACESWO)
PB4(NJTRST)
PB5
PB6
PB7
ADC12_IN8
ADC12_IN9
protection2_out3
protection2_out4
JTAG_TDO
JTAG_RESET
PA8
PA9
PA10
PA11
PA12
PA13(JTMS-SWDIO)
PA14(JTCK-SWCLK)
PA15(JTDI)
JTAG_SWIO
JTAG_SWCLK
JTAG_TDI
PB8
PB9
PB10
PB11
PB12
PB13
PB14
PB15
protection1_out9
protection1_out10
protection1_out11
protection1_out12
protection2_out1
protection2_out2
MCU_TX
MCU_RX
ADC123_IN10
ADC123_IN11
ADC123_IN12
ADC123_IN13
ADC12_IN14
ADC12_IN15
USART6_TX
USART6_RX
PC0
PC1
PC2
PC3
PC4
PC5
PC6
PC7
PD0
PD1
PD2
PD3
PD4
PD5
PD6
PD7
PC8
PC9
PC10
PC11
PC12
PC13
PC14-OSC32_IN(PC14)
PC15-OSC32_OUT(PC15)
PD8
PD9
PD10
PD11
PD12
PD13
PD14
PD15
STM32F427ZIT6
U1B
PE0
PE1
PE2
PE3
PE4
PE5
PE6
PE7
PF0
PF1
PF2
PF3
PF4
PF5
PF6
PF7
ADC3_IN9
ADC3_IN14
ADC3_IN15
ADC3_IN4
ADC3_IN5
protection2_out5
protection2_out6
protection2_out7
protection2_out8
protection2_out9
PE8
PE9
PE10
PE11
PE12
PE13
PE14
PE15
PF8
PF9
PF10
PF11
PF12
PF13
PF14
PF15
ADC3_IN6
ADC3_IN7
ADC3_IN8
protection2_out10
protection2_out11
protection2_out12
Add crystal oscillator
PG0
PG1
PG2
PG3
PG4
PG5
PG6
PG7
PH0-OSC_IN(PH0)
PH1-OSC_OUT(PH1)
BOOT0
NRST
PDR_ON
GND
VDD
PG8
PG9
PG10
PG11
PG12
PG13
PG14
PG15
VCAP_1
VCAP_2
STM32F427ZIT6
C1
2.2µF
C2
2.2µF
GND
GND

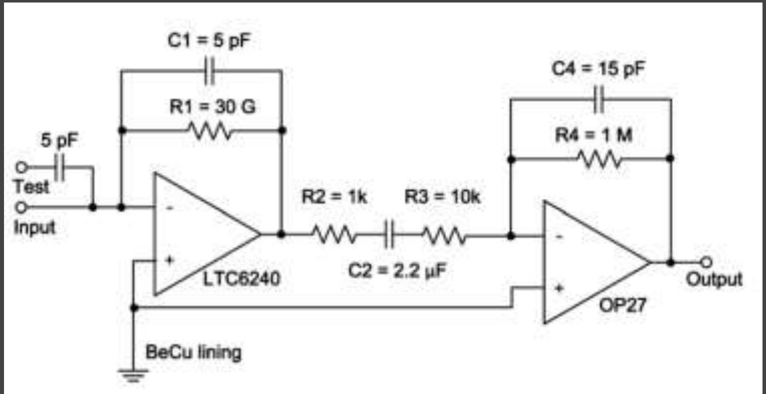
MCU IO


VDD
VDD
P2
MCU_VCC
GND
TDI
SWIO
SWCLK
NC
TDO
RESET
NC
NC
MCU_VCC
GND
GND
GND
GND
GND
GND
NC
GND
GND
JTAG_TDI
JTAG_SWIO
JTAG_SWCLK
JTAG_TDO
JTAG_RESET
GND
GND
JTAG_Header
JTAG Programming


VDD
C3 0.10µF
C4 0.10µF
C5 0.10µF
C6 0.10µF
C7 0.10µF
C8 0.10µF
C9 0.10µF
C10 0.10µF
C11 0.10µF
C12 0.10µF
C13 0.10µF
C14 0.10µF
C15 0.10µF
GND
AGND
C18 1µF
C19 4.7µF
U1C
VBAT
VREF+
3V3_Ref
VDD
VSS
VDDA
VSSA
STM32F427ZIT6
U2
OUT
IN
REF2933AIDBZR
C16 0.10µF
C17 1µF
MCU Power

CSA Circuit (Given)

- Given by the client as a low noise method to translate a charge induced on a wire electrode into an amplified voltage
- The first op-amp is a charge sensitive preamplifier with gain of 1/C1
- Second is an AC coupled voltage amplifier with a gain of 91



$$\text{Sensitivity} = \frac{1}{C_1} \times 91 = 18\text{mV}/\text{C}$$

ADC resolution will be much greater than needed

ARS Power Budget

ITLL and other similar power supplies have a max current of 5A

Component	**Quantity**	**Max Current Draw (mA)**
Teensy	1	60.2
Motor/Motor Driver	1*	2000
Photodiode Circuit	13	5.72
		2065.92mA (~2.07A)

*Note: while there are four motor/motor drivers sets, only one will be utilized at any given time

Photodiode Noise Analysis

Default sampling rate of ADC Δf = 1Hz
Transimpedance amplifier resistance R = 330kΩ
Room temperature T = 296K

$$V_{rms} = \sqrt{4k\pi RT\Delta f}$$

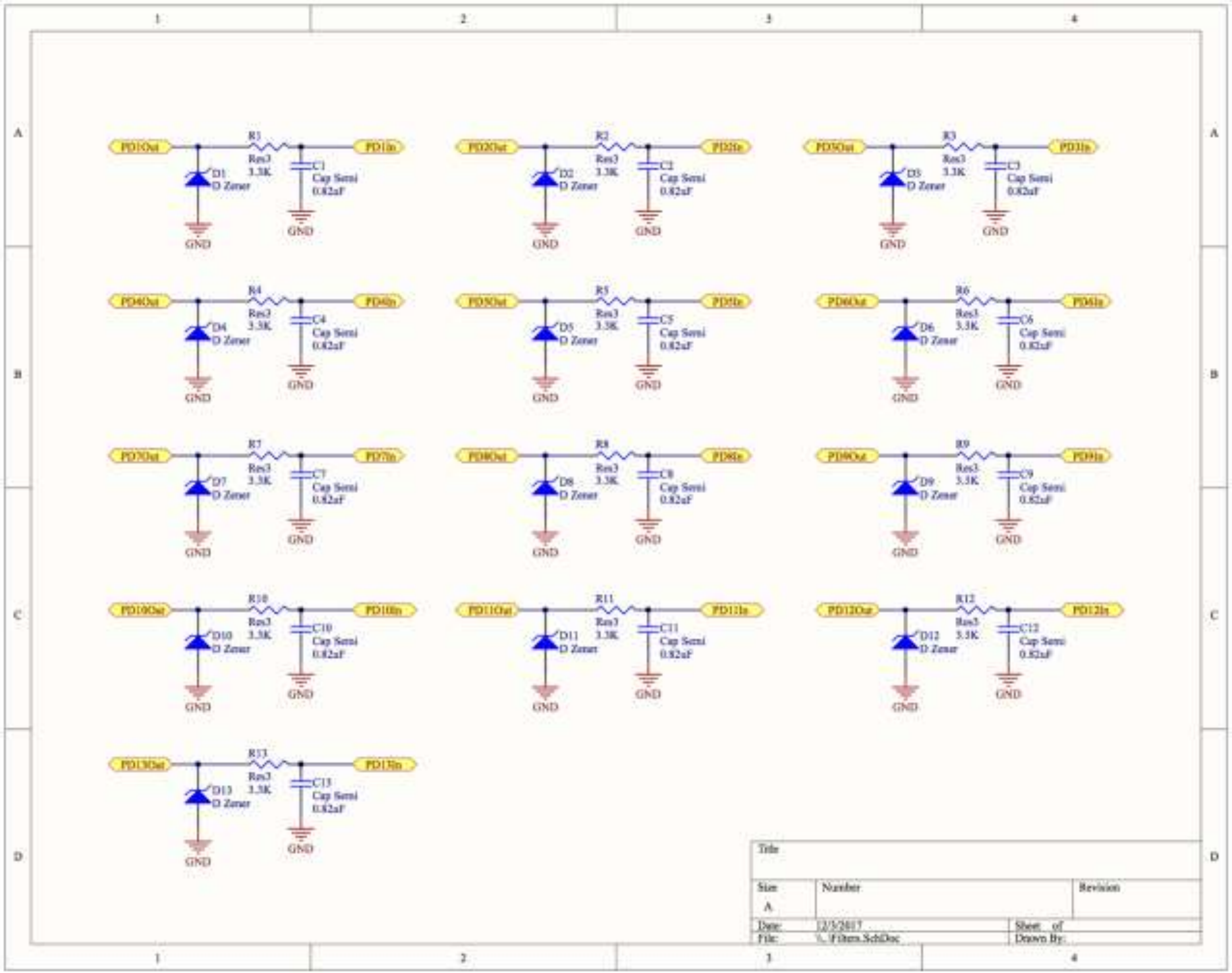
=

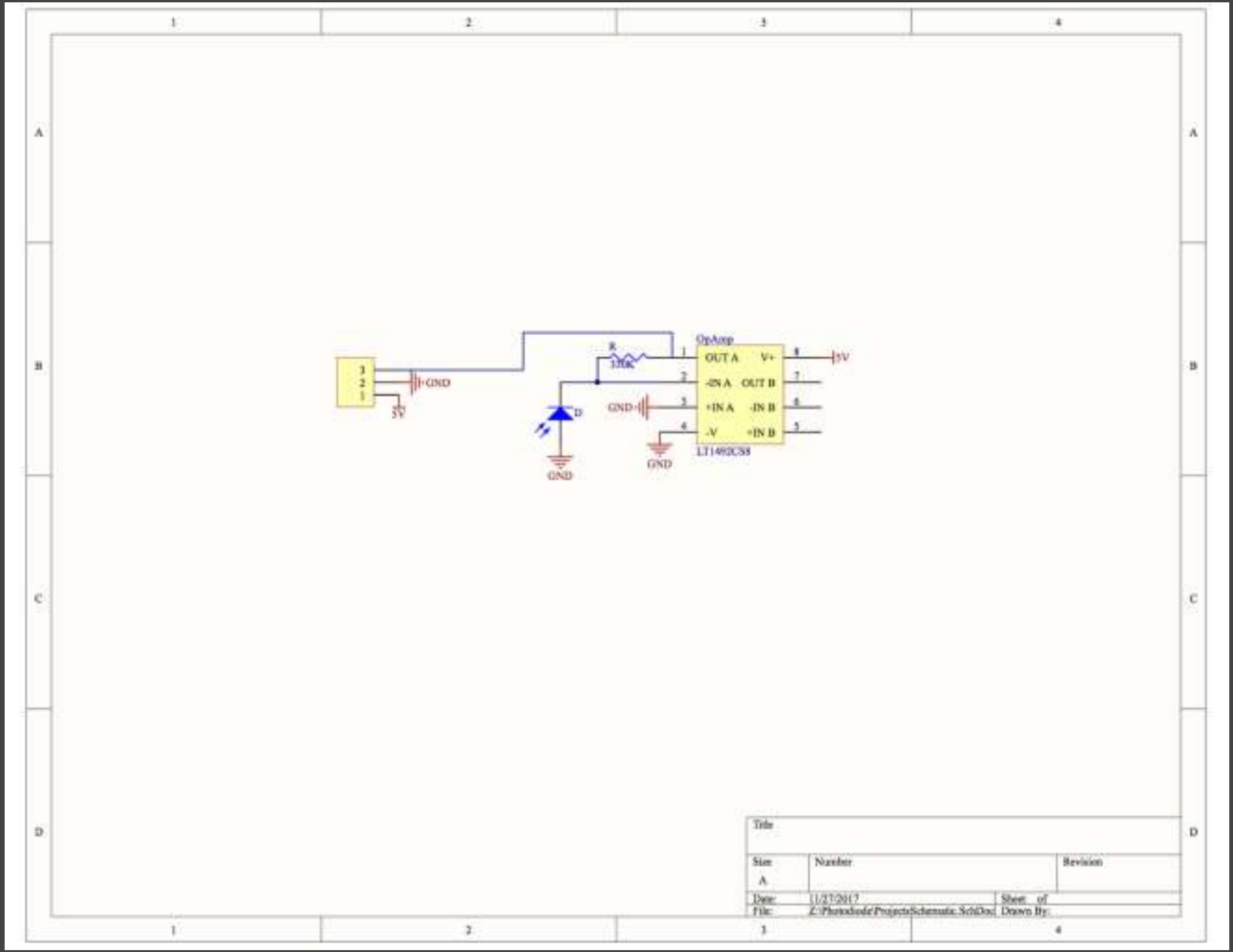
73.4u∀$_{rms}$

Laboratory cutoff frequency f_c = 60Hz
For typical resistor value R = 3.3kΩ

$$f_c = \frac{1}{2\pi RC}$$

→ C = 0.82uF


1
2
3
4
A
B
C
D
PD1Out
R1
Res3
3.3K
PD1In
D1
D Zener
C1
Cap Semi
0.82uF
GND
PD2Out
R2
Res3
3.3K
PD2In
D2
D Zener
C2
Cap Semi
0.82uF
GND
PD3Out
R3
Res3
3.3K
PD3In
D3
D Zener
C3
Cap Semi
0.82uF
GND
PD4Out
R4
Res3
3.3K
PD4In
D4
D Zener
C4
Cap Semi
0.82uF
GND
PD5Out
R5
Res3
3.3K
PD5In
D5
D Zener
C5
Cap Semi
0.82uF
GND
PD6Out
R6
Res3
3.3K
PD6In
D6
D Zener
C6
Cap Semi
0.82uF
GND
PD7Out
R7
Res3
3.3K
PD7In
D7
D Zener
C7
Cap Semi
0.82uF
GND
PD8Out
R8
Res3
3.3K
PD8In
D8
D Zener
C8
Cap Semi
0.82uF
GND
PD9Out
R9
Res3
3.3K
PD9In
D9
D Zener
C9
Cap Semi
0.82uF
GND
PD10Out
R10
Res3
3.3K
PD10In
D10
D Zener
C10
Cap Semi
0.82uF
GND
PD11Out
R11
Res3
3.3K
PD11In
D11
D Zener
C11
Cap Semi
0.82uF
GND
PD12Out
R12
Res3
3.3K
PD12In
D12
D Zener
C12
Cap Semi
0.82uF
GND
PD13Out
R13
Res3
3.3K
PD13In
D13
D Zener
C13
Cap Semi
0.82uF
GND
Title
Size
A
Number
Revision
Date:
12/5/2017
Sheet of
File:
\..\Filters.SchDoc
Drawn By:



OpAmp
R
OUT A
V+
-IN A
OUT B
+IN A
-IN B
-V
+IN B
LT1492CS8
GND
5V
D
Title
Size
A
Number
Revision
Date: 11/27/2017
Sheet of
File:
Drawn By:

Data buffering runtime

The ADC data will end up in a predetermined location in memory from the DMA controller

It then needs to be moved to the buffer

Minimum:

104 cycles (~2.6 μs)

Explanation	Number of instructions	Cycles per instruction	Total Clock Cycles
Load all 24 channels	24	2	48
Check for buffer rollover	2	1	2
Branch in rollover case	1	4	4
Divide to get remainder	1	1	1
Add/subtract index	1	1	1
Store all 24 channels to buffer	24	2	48

Event Filter Runtime

$Y[n] = 2Y[n-1] - Y[n-2] + X[n] - 2X[n-W/4] + 2X[n-3W/4] - X[n-W]$

Assume circular buffer data structures and 12 wires **Minimum: 660 cycles (~4 µs)**

Explanation	Number of instructions	Cycles per instruction	Total Clock Cycles
Load X/Y values	6 x 12	2	144
Multiply by scale factors	3 x 12	1	36
Add/subtract X/Y values	5 x 12	1	60
Check for buffer rollover	10 x 12	1	120
Branch in rollover case	5 x 12	4	240
Divide to get remainder	5 x 12	1	60
Add/subtract index	5 x 12	1	60

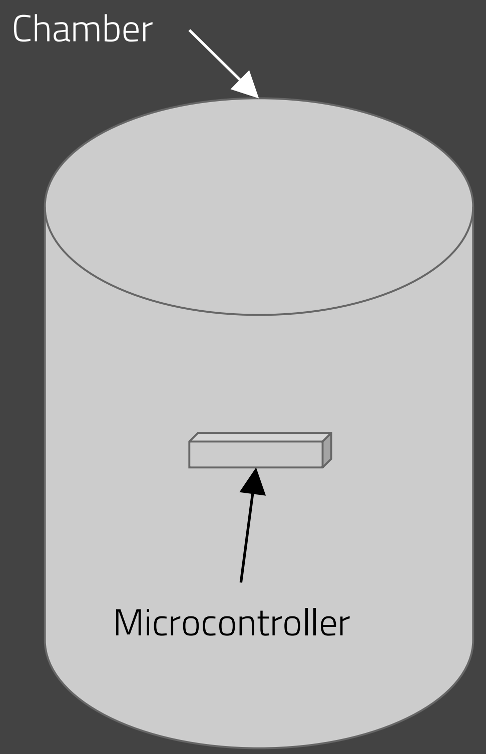
Event Trigger Threshold Runtime

Worst-case threshold check (no trigger)
112 cycles (~0.6 μs)

Minimum:

Explanation	Number of instructions	Cycles per instruction	Total Clock Cycles
Load all filter outputs	1 x 12	2	24
Compare high threshold	2 x 12	1	24
Load all filter outputs	1 x 12	2	24
Compare adjacent wires	4 x 10	1	40

Thermal



Assumptions:

- Chamber is very large relative to microcontroller (black body)
- Chamber walls at constant 293.15 K
- Microcontroller is a black body

$$\dot{q}_{in} = \dot{q}_{out}$$

$$\sigma A_{micro} T_{chamber}^4 + P_{micro} = \sigma A_{micro} T_{micro}^4$$

$$(5.67e-8)(2)(.07)^2(293.15)^4 + 0.5 = (5.67e-8)(2)(.07)^2 T_{micro}^4$$

$$T_{micro} = 301.7K$$

Budget Backup Slides

Instrument Hardware Cost (Analog)

ITEM	UNIT COST ($)	# REQUIRED	TOTAL COST ($)
LTC6240 OpAmp	1.2	30	36
OP275 OpAmp	3	15	45
10 GΩ Resistors	9.5	90	855
5 pF Capacitor	0.1	60	6
15 pF Capacitor	0.5	30	15
2.2 μF Capacitor	0.2	30	6
1kΩ Resistor	0.1	30	3
10 kΩ Resistor	0.1	30	3
1 MΩ Resistor	0.1	30	3
PCB	66	1	66
Misc.			50
Total			1038

Instrument Electronics Cost (Digital)

ITEM	UNIT COST ($)	# REQUIRED	TOTAL COST ($)
Development Board	40	1	40
Microcontroller	15	2	30
PCB	66	1	66
Peripherals			30
Support Programmer	100	1	100
Total			40-226

ARS Mechanisms Cost

ITEM	UNIT COST ($)	# REQUIRED ($)	TOTAL COST ($)
Servo Motors	50	2	100
Stepper Motors	20	2	40
12"x12"x1/8" 6061 Aluminum	20	3	60
3/16"x12" 6061 Al Rod	5	1	5
Gear Rack	50	1	50
Gears	50	4	200
Rack Rail	10	1	10
Misc Mounting Equipment			100
Testing Equipment			100
Total			665

ARS Sun Sensing Cost

ITEM	UNIT COST ($)	# REQUIRED	TOTAL COST ($)
Photodiodes	5	20	100
Microcontroller (Teensy 3.6)	50	1	50
PCB	66	1	66
Peripherals			50
Accelerometer	20	1	20
Misc (cables, etc)			50
Total			336

CubeSat Structure Cost

ITEM	UNIT COST ($)	# REQUIRED	TOTAL COST ($)
12"x24" 0.125" Thickness 6061 T6 Al Sheet	35	1	35
24"x24" 0.125" Thickness 6061 T6 Al Sheet	30	1	30
Misc			100
Total			165

Instrument Structure Cost

ITEM	UNIT COST ($)	# REQUIRED	TOTAL COST ($)
0.3125" Thick, 24"x24" 6061 Al	140	1	140
0.04" Thick, 12"x12" 6061 Al	6	1	6
0.02" Copper Wire 1/4lb spool	7	1	7
M4 Screws	17	8	136
0.04" Thick, 12"x12" 6061 Al	6	1	6
0.04" Thick, 12"x12" 6061 Al	6	1	6
3/8"x3/8"x12" Delrin Bar (Black)	3	1	3
Polished 6061 0.125" Thick, 12"x12" plate	45	1	45
Magnets			100
Total			449

Project Scope

- TRL 4
  - Integration of different components
  - Validation in laboratory environment
  - Do not have to design for intended environment