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

Spring Final Review

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Customer: Dr. Xu Wang, Dr. Zoltan Sternovsky

Advisor: Dr. Torin Clark

Overview

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Design
Test Overview
Test Results
Systems Engineering
Project Management

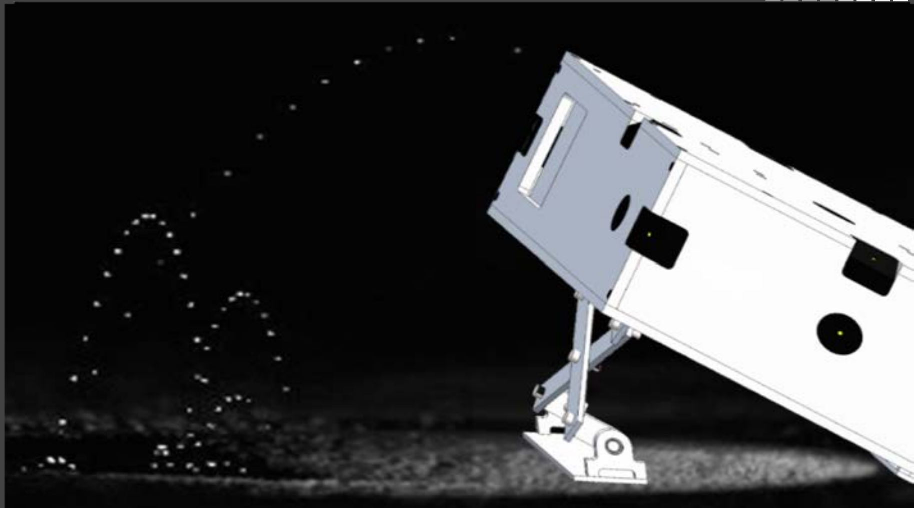
Project Motivation

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

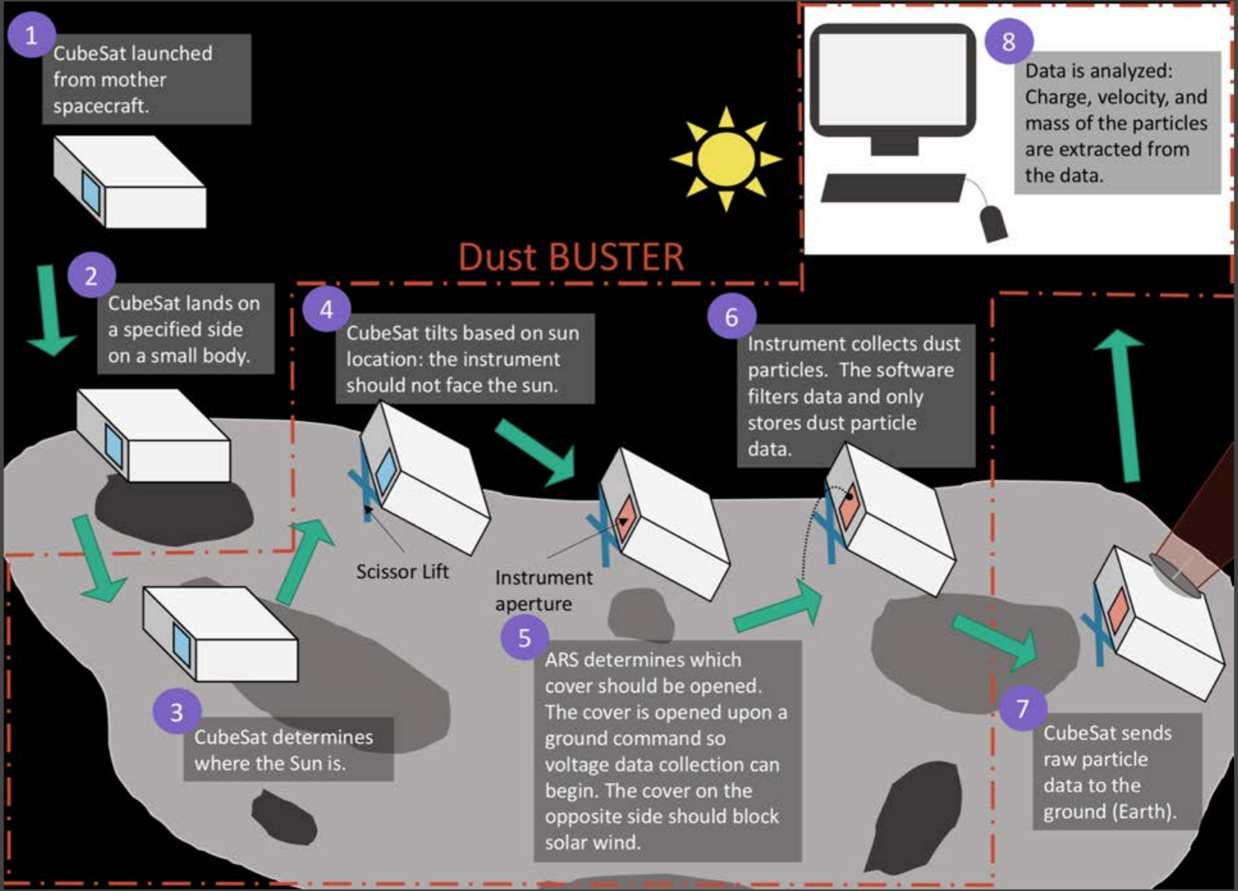


Project Statement

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



1 CubeSat launched from mother spacecraft.

2 CubeSat lands on a specified side on a small body.

3 CubeSat determines where the Sun is.

4 CubeSat tilts based on sun location: the instrument should not face the sun.

5 ARS determines which cover should be opened. The cover is opened upon a ground command so voltage data collection can begin. The cover on the opposite side should block solar wind.

6 Instrument collects dust particles. The software filters data and only stores dust particle data.

7 CubeSat sends raw particle data to the ground (Earth).

8 Data is analyzed: Charge, velocity, and mass of the particles are extracted from the data.

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

Design

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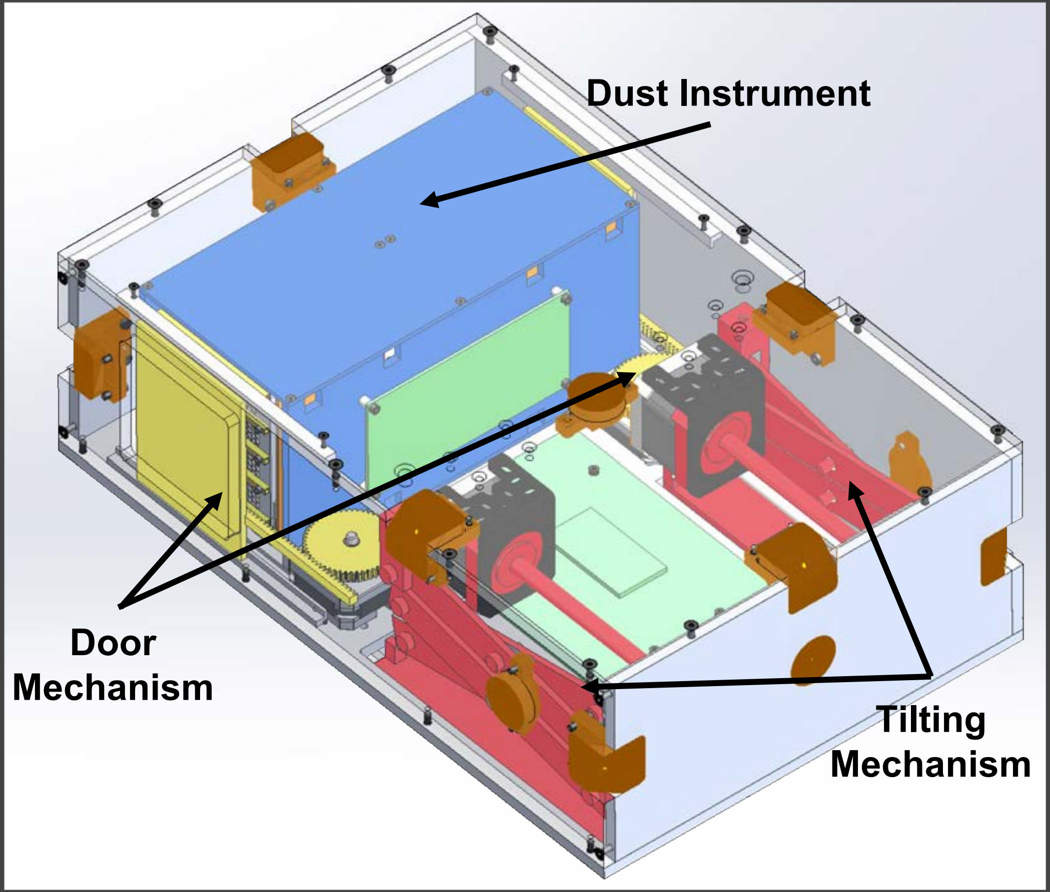
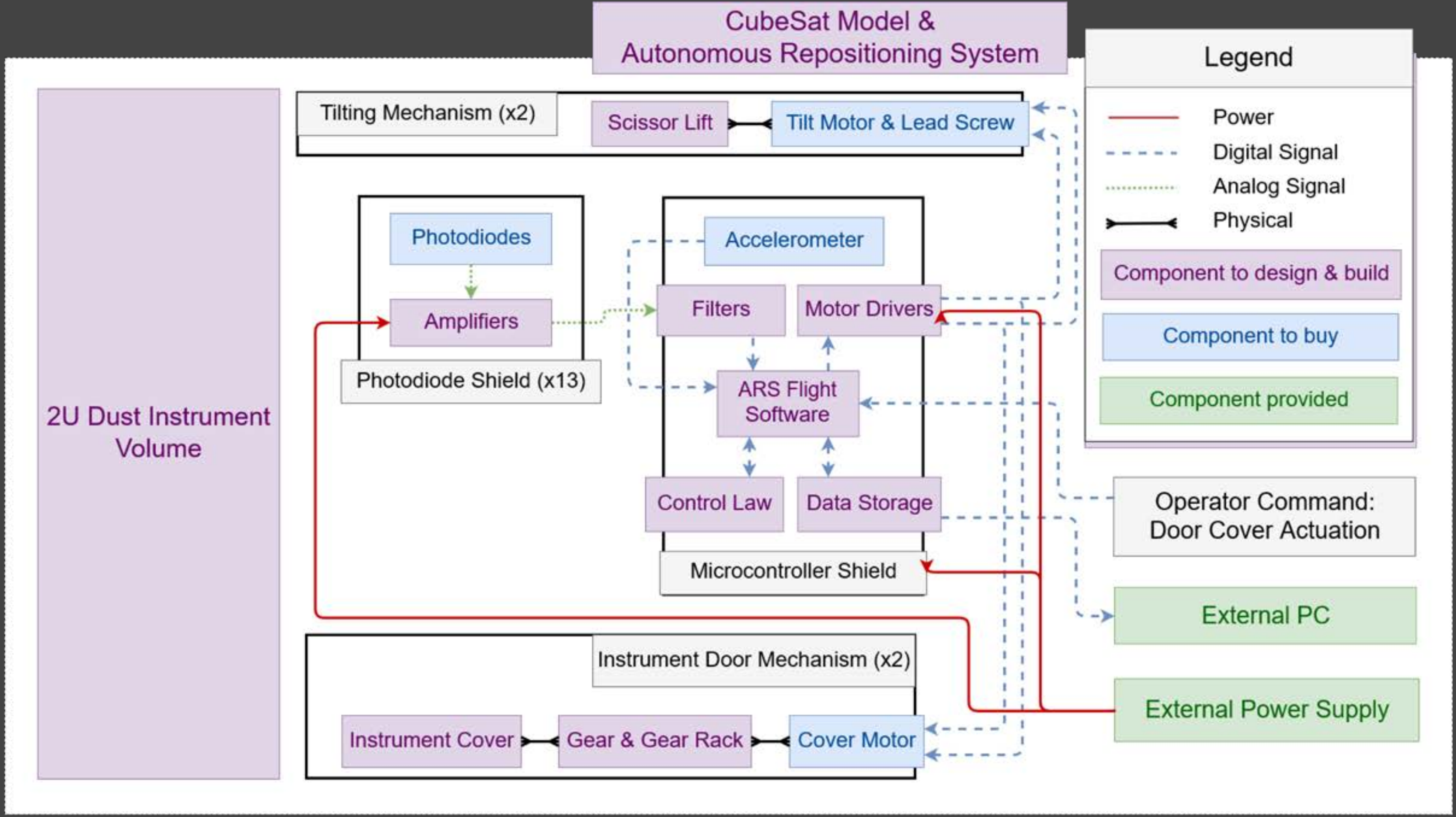
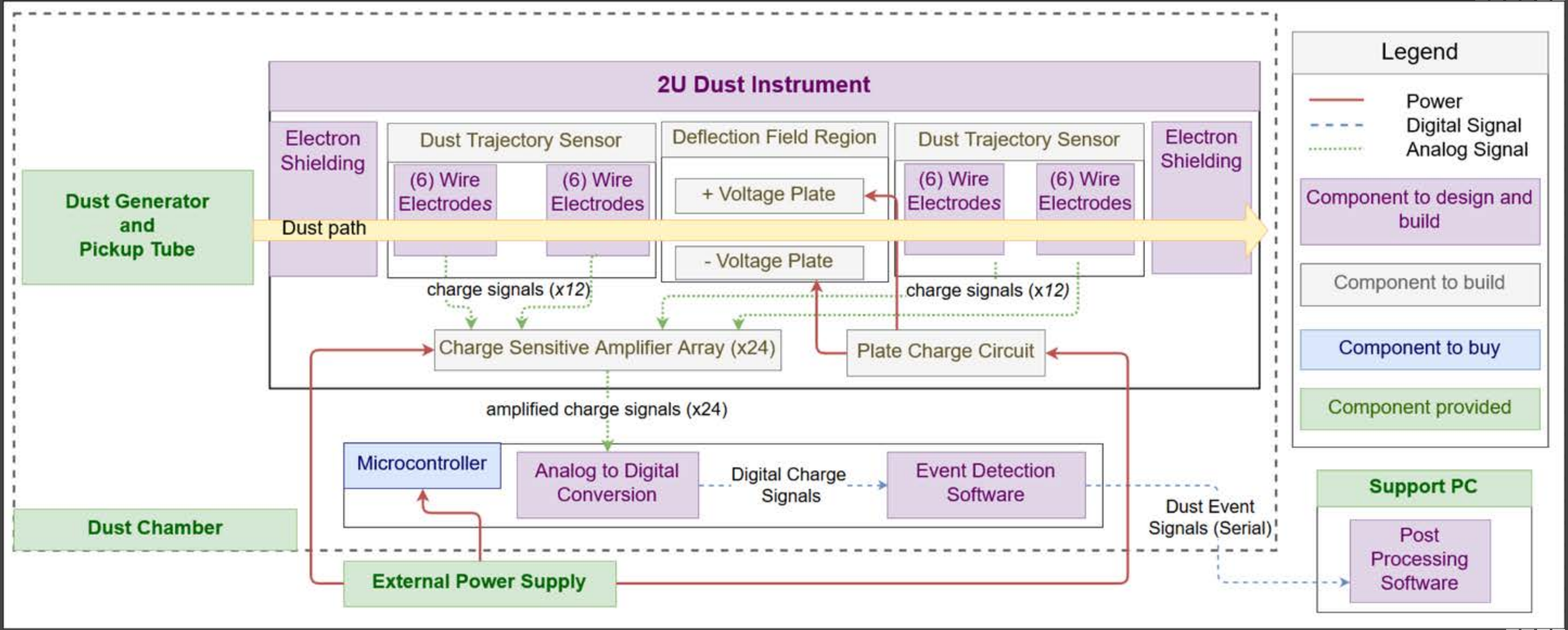
Design Recap



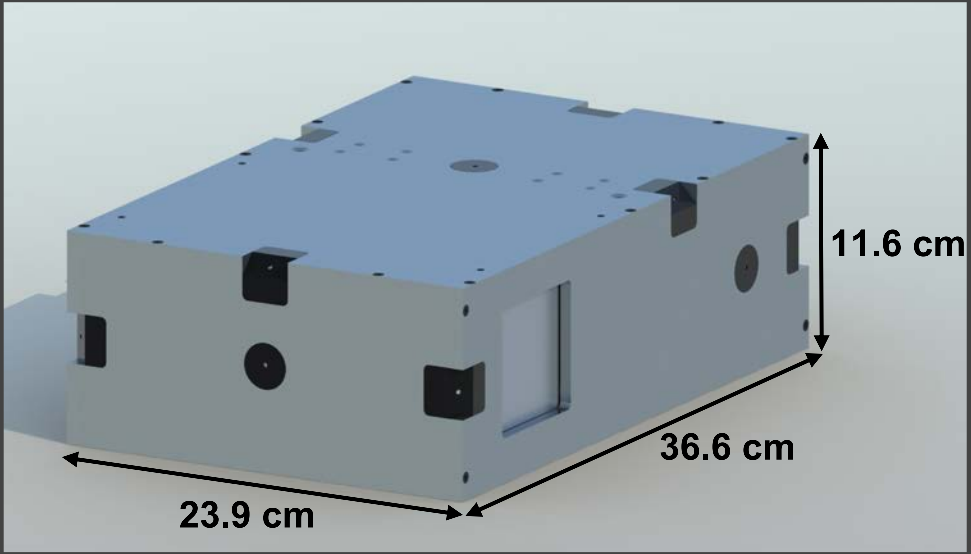
Autonomous Repositioning System FBD



Instrument Functional Block Diagram

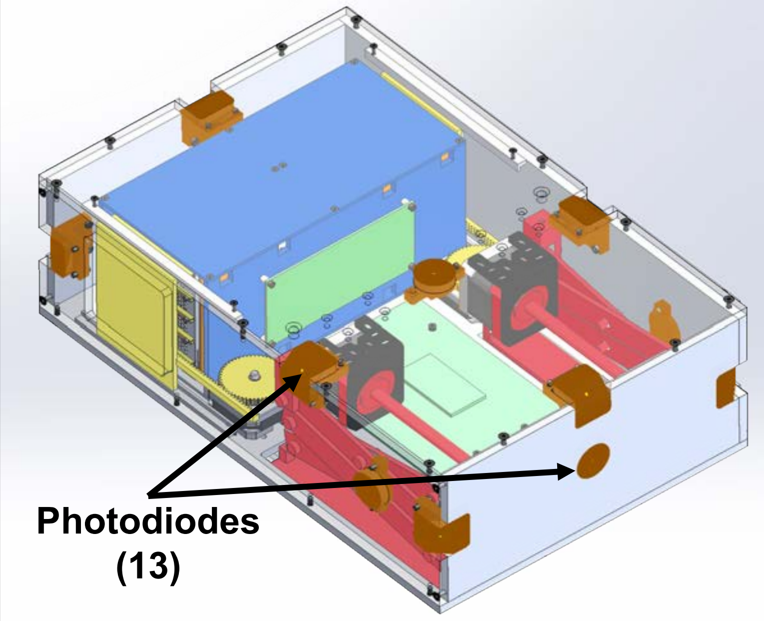


Design Recap - CubeSat Model



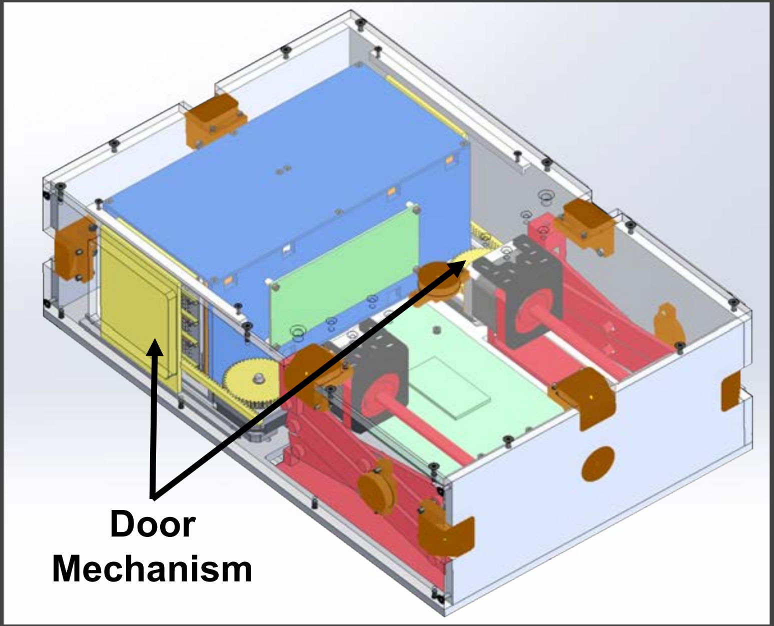
- Material: T-6061 aluminum
- Mass: 8.41 kg (with all systems)
- Dimensions: 23.9 x 36.6 x 11. 6 cm

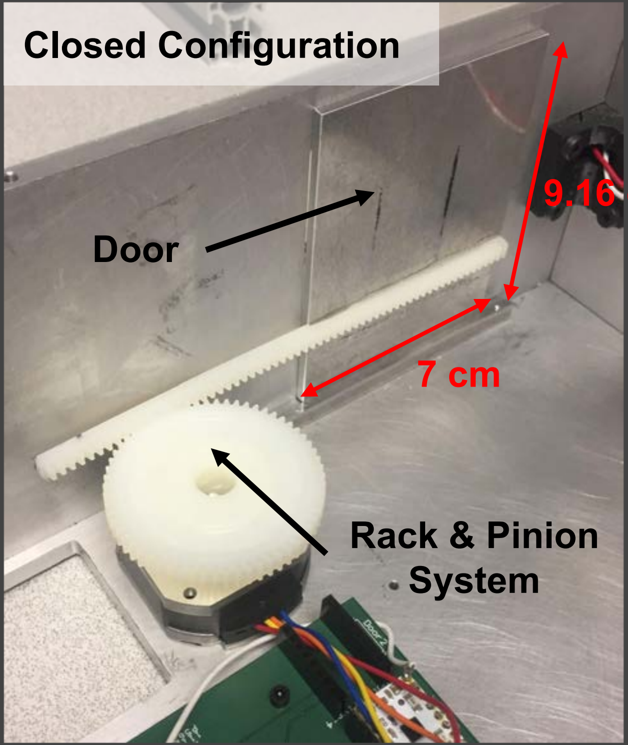
Design Recap – Photodiodes



- Material: Formlabs stereolithography resin
- Mass: 0.16 kg (total)

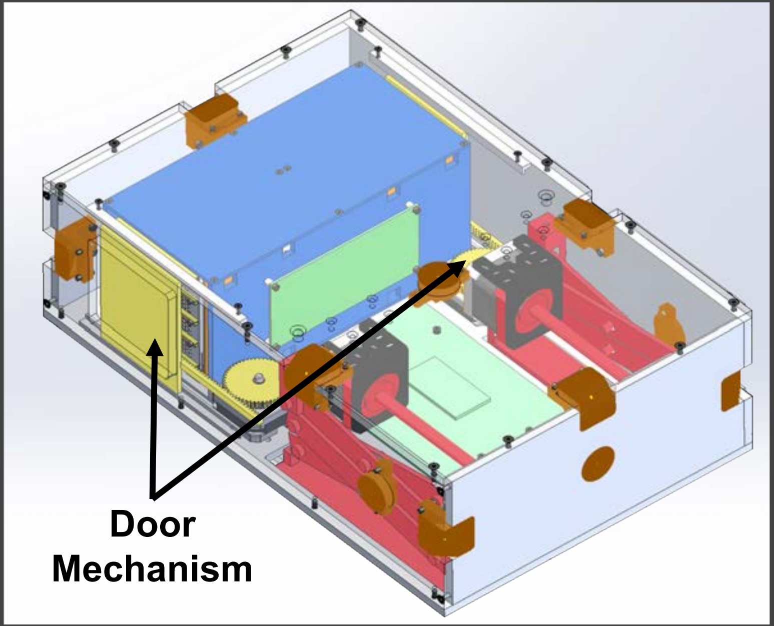
Design Recap - Door Mechanism





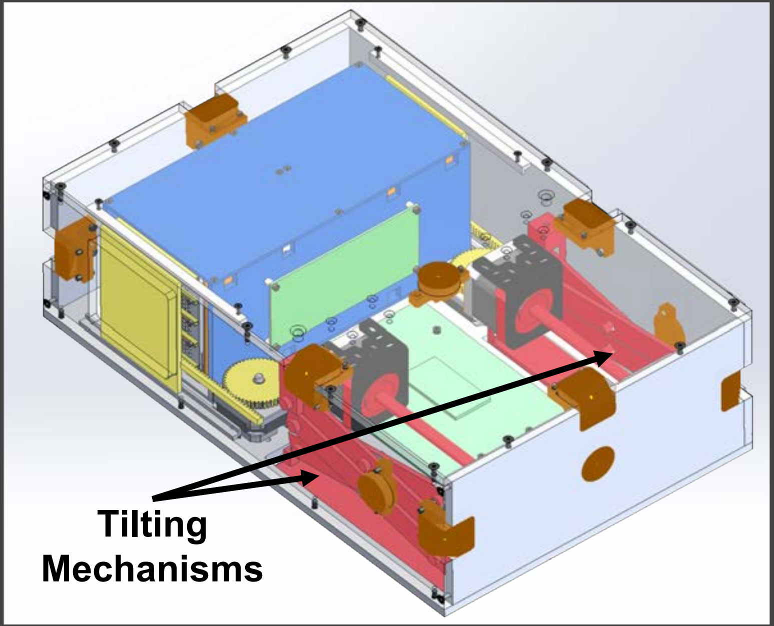
- Material: Aluminum, nylon
- Mass: 0.84 kg (total)

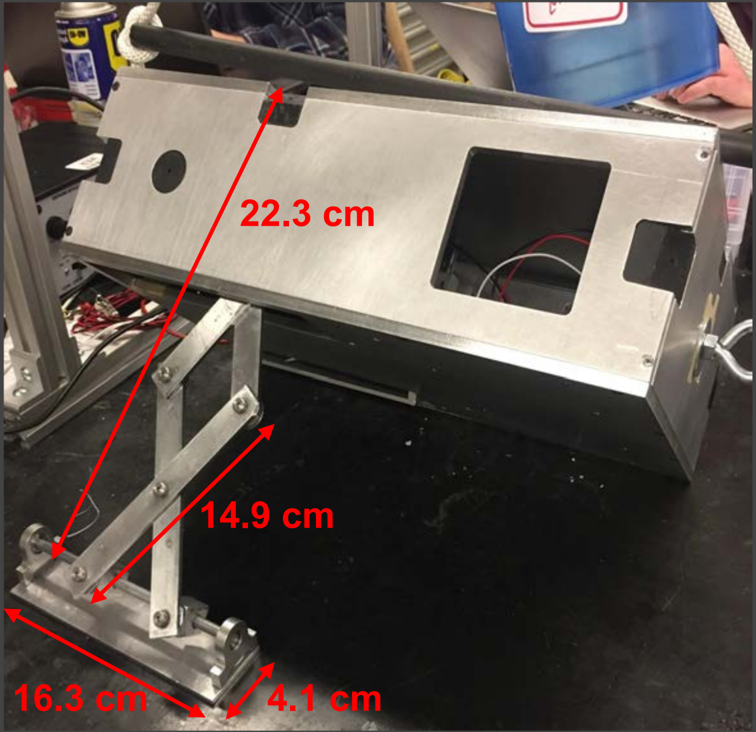
Design Recap - Door Mechanism



- Material: Aluminum, nylon
- Mass: 0.84 kg (total)

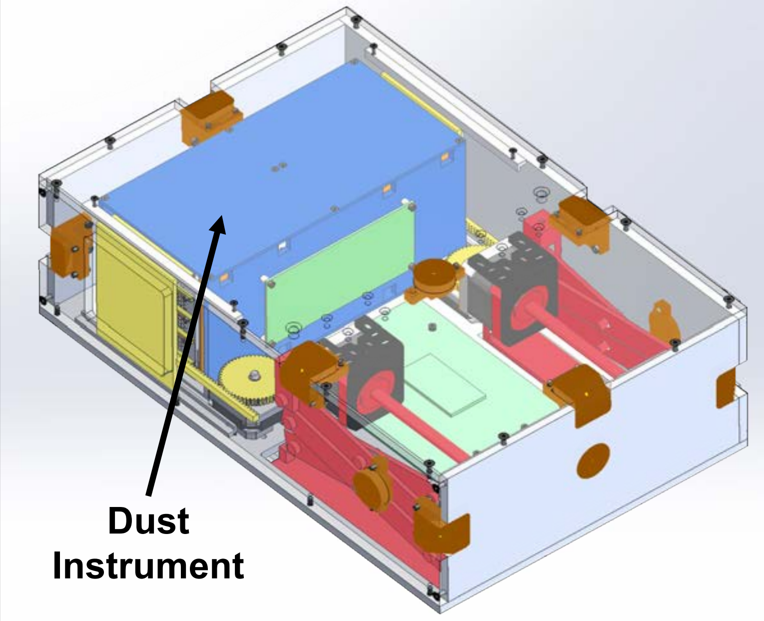
Design Recap - Scissor Lift

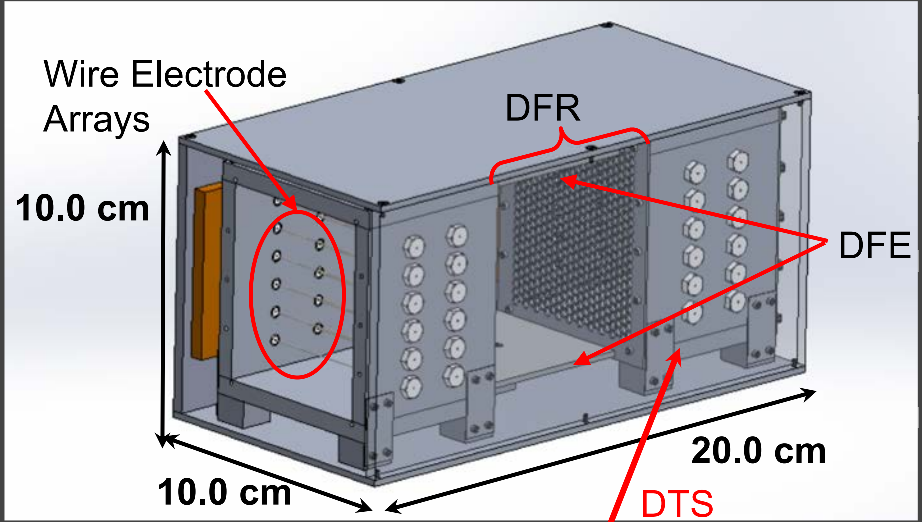


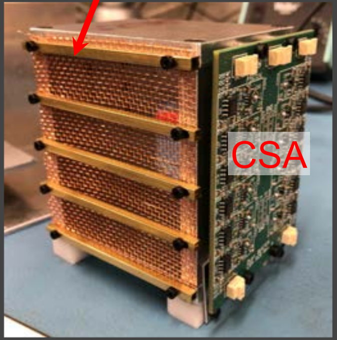


- Material: Aluminum
- Mass: 1.32 kg (total)

Design Recap - Dust Instrument







- Material: Aluminum, Delrin, PEEK, Stainless steel, Copper
- Mass: 1.47 kg

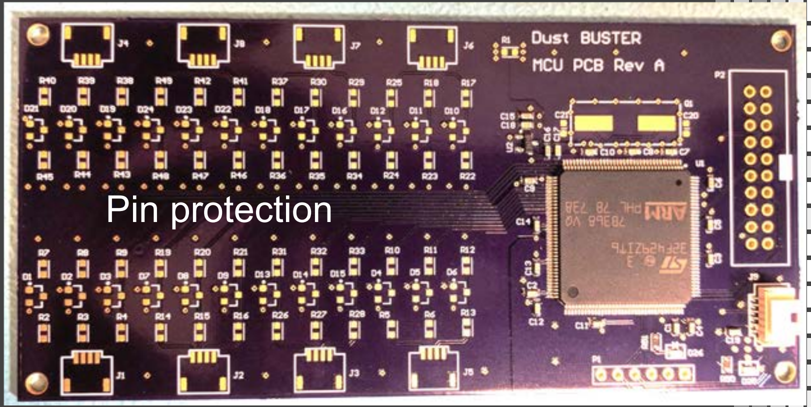
Design Recap - Embedded Systems

Microcontroller PCB:

- Handles inputs from all 24 wire electrodes
- Runs real-time software
- Includes protection circuits

Real-time Software:

- Samples all 24 wire electrodes real-time
- Runs triggering software
- Outputs data over serial


STM32F429ZIT6 Microcontroller

Pin protection

Critical Project Elements

Critical Project Element	Relation to Project Success
Surviving Impact	Wire electrodes must survive impact to collect data
Sun determination	Need Sun location to collect good dust data
Tilting mechanism	Tilt required to let dust enter instrument
Real-time event detection	Event detection required to output the correct data

Test Overview

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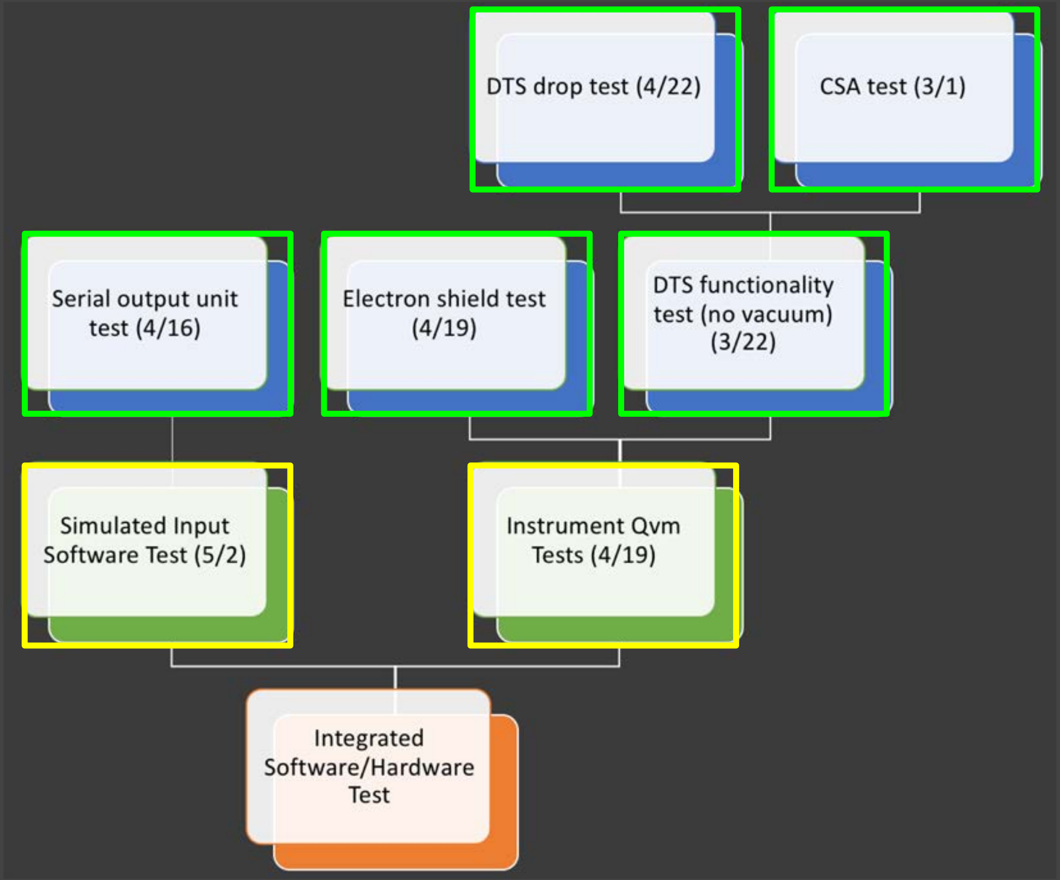
Instrument Testing Flow

Complete

In Progress


DTS drop test (4/22)

CSA test (3/1)

Serial output unit test (4/16)

Electron shield test (4/19)

DTS functionality test (no vacuum) (3/22)

Simulated Input Software Test (5/2)

Instrument Qvm Tests (4/19)

Integrated Software/Hardware Test

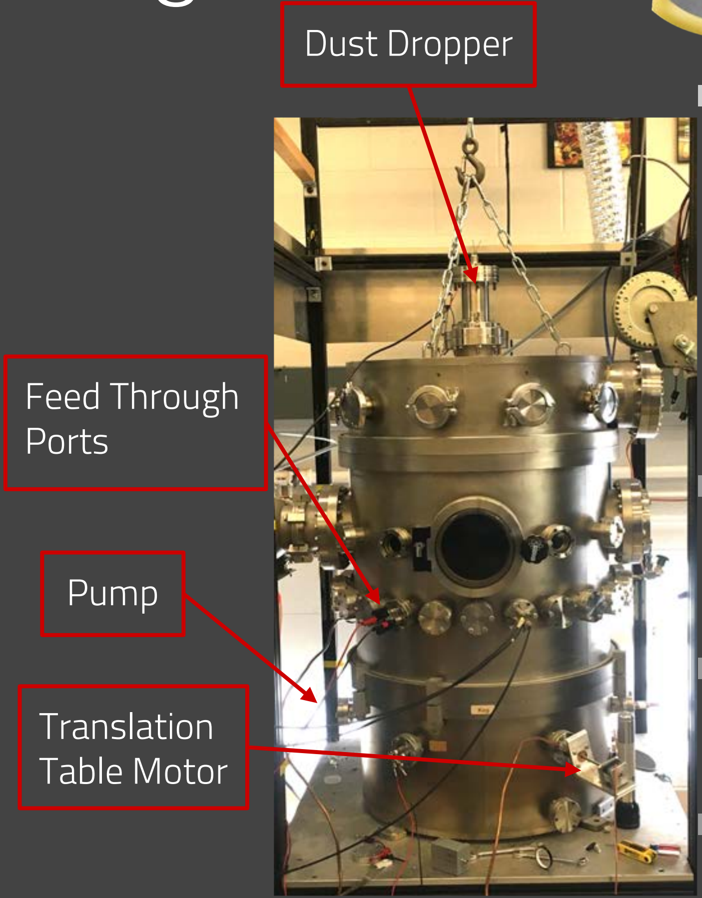
Impact Testing

Location	Idea Forge
Equipment	● Lansmont 15D shock test machine ● Crossbow CXL10LP3 Accelerometer ● DTS unit ● DAQ and LabView VI
Data Out	● Acceleration data ○ Integrate for impact velocity ● Inspect wire electrodes to determine if broken ● Iterate at higher impact velocities
Requirements Verified	● SR 2.5: Instrument wire electrodes shall remain intact after a 10 m/s impact on a rigid surface.

Lansmont Machine

IMPACT Lab Testing

Location	IMPACT Lab (CU East Campus)
Equipment (Customer Provided)	● Vacuum chamber (w/ pump) ● Vacuum wall cable interfaces ● Dust dropper ● Free electron emitter ● Power supplies (±2.5V, ±15V, ±5kV) ● Data acquisition system ● Translation table
Data Out	● Analog voltages ○ One set each for charge (Q), velocity (v), and mass (m)
Requirements Verified	● FR 2: Detect dust particles that enter the instrument ● FR 5: Collect dust signals and issue commands to and from the instrument and ARS ● FR 6: Process data and detect dust events



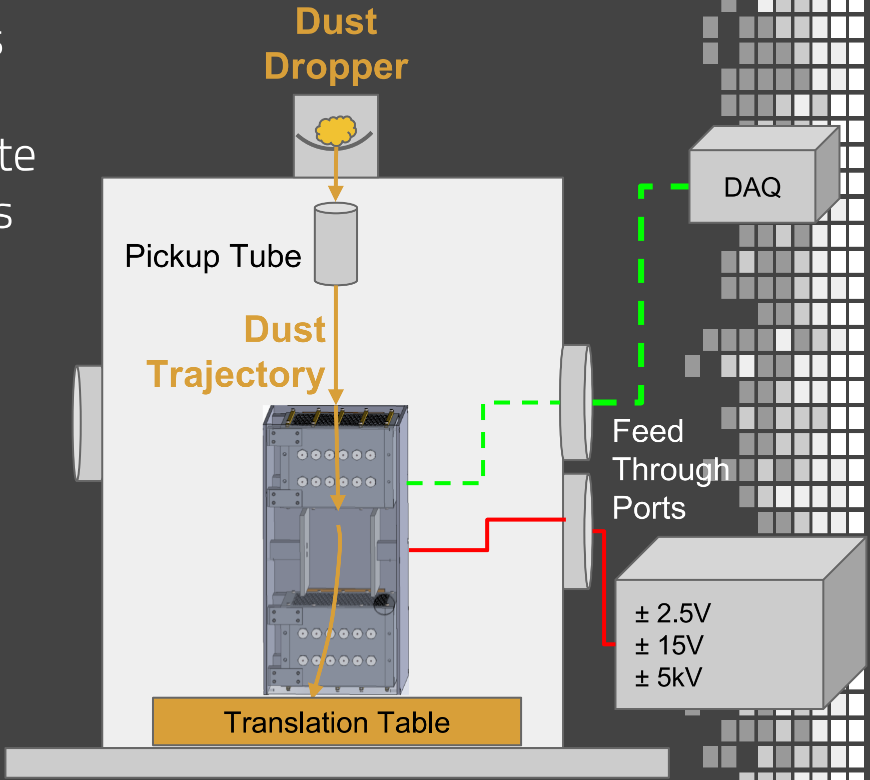
Full Instrument Test Modifications

Software difficulties required modification to test set-up to be able to verify requirements

7-channel DAQ will be used to collect data

Charge will be independently verified separate from mass and velocity in two different tests due to limited number of DAQ inputs

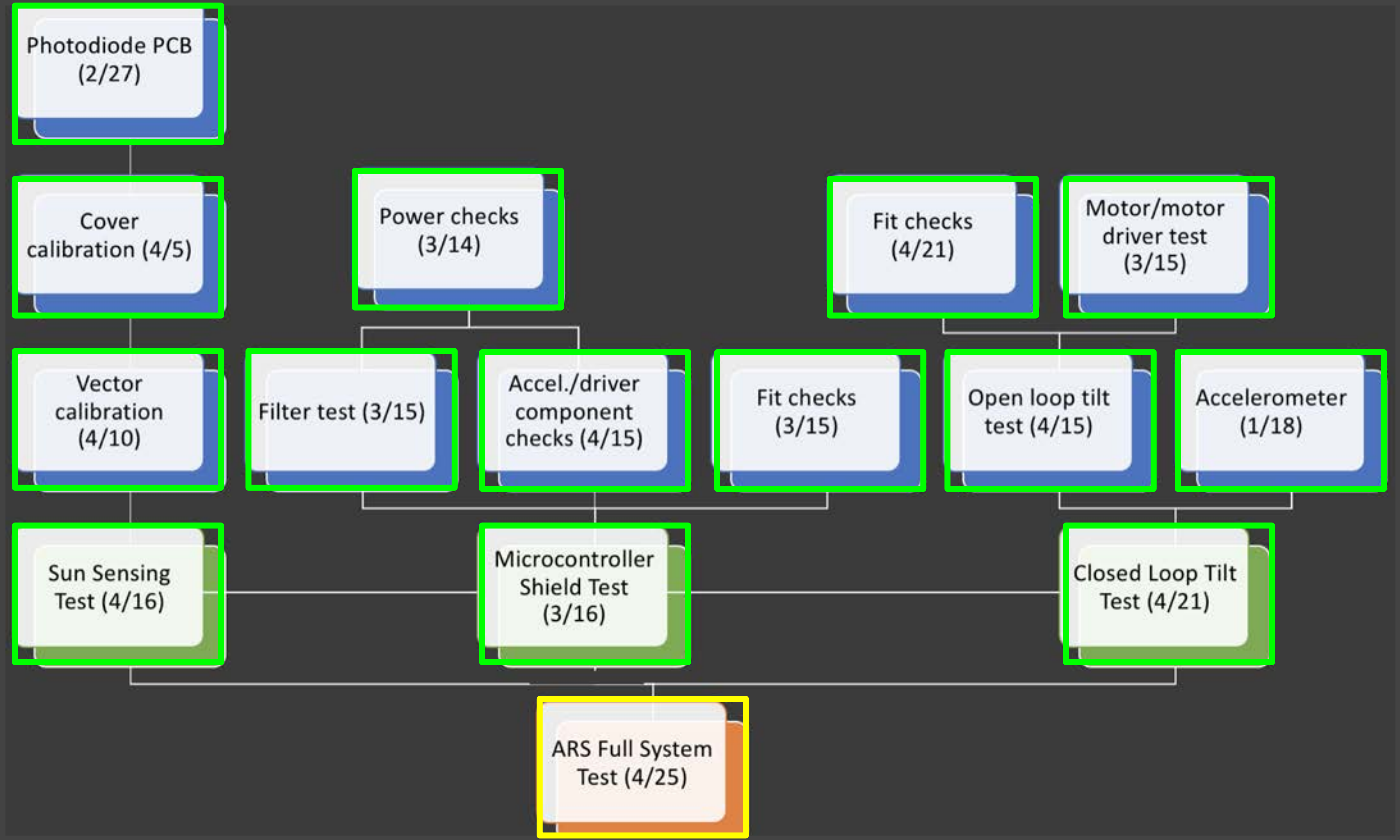
Data Type	Setup
Charge (Q)	One electrode plane
Mass (*m*)	Subset of channels from all four planes
Velocity (*v*)	Two electrode planes in one DTS



ARS Testing Flow

Complete

In Progress



Photodiode PCB (2/27)

Cover calibration (4/5)

Power checks (3/14)

Fit checks (4/21)

Motor/motor driver test (3/15)

Vector calibration (4/10)

Filter test (3/15)

Accel./driver component checks (4/15)

Fit checks (3/15)

Open loop tilt test (4/15)

Accelerometer (1/18)

Sun Sensing Test (4/16)

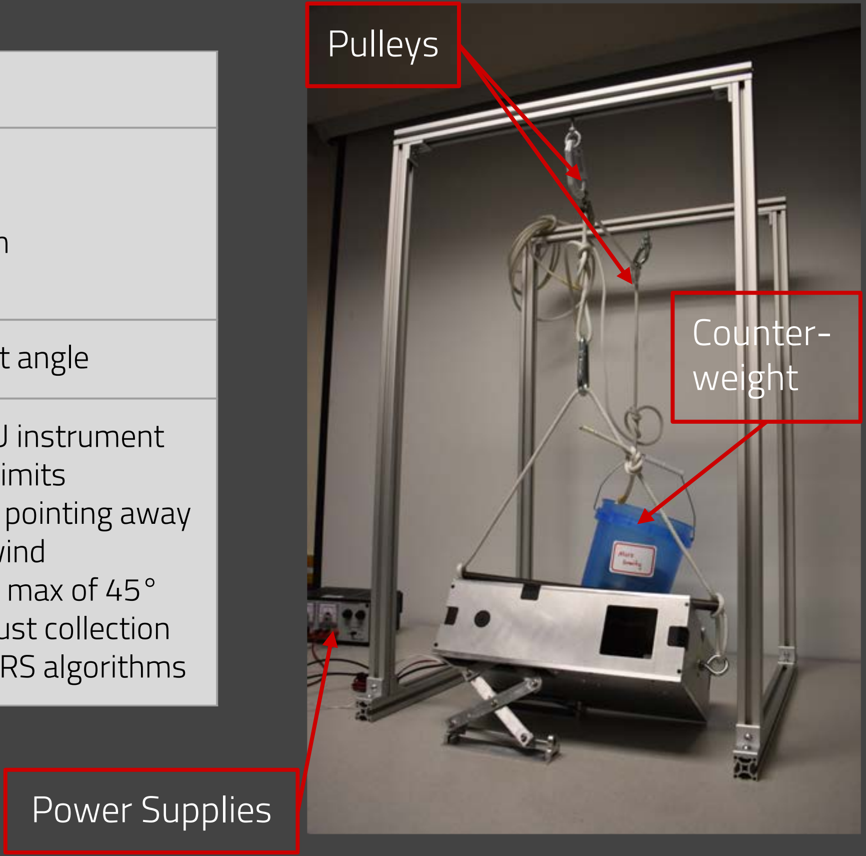
Microcontroller Shield Test (3/16)

Closed Loop Tilt Test (4/21)

ARS Full System Test (4/25)

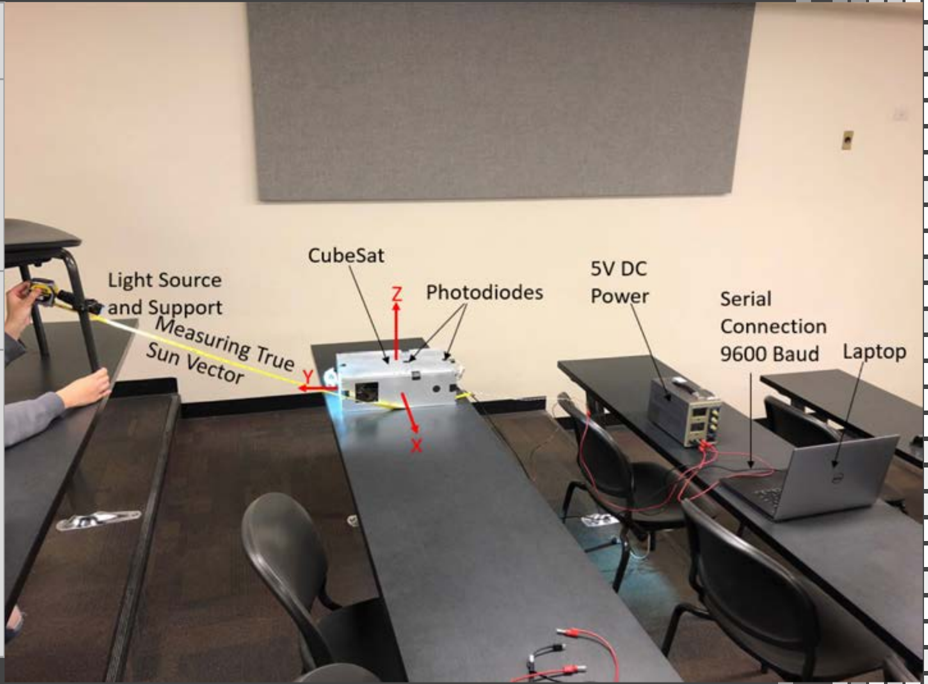
ARS Tilt Testing

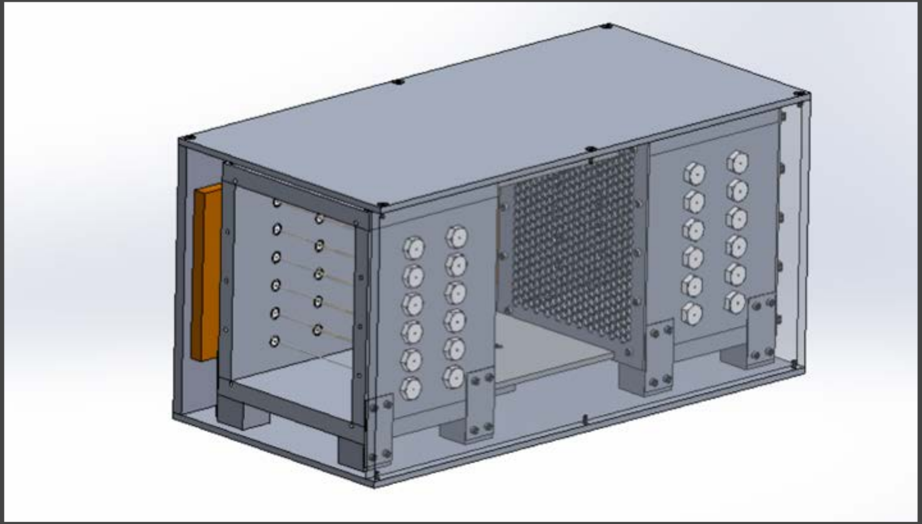
Location	Senior Projects Depot
Equipment	• Fully assembled CubeSat • Power supply (5V and 3V) • Pulley/counterweight system • PC
Data Out	• Commanded and achieved tilt angle
Requirements Verified	• FR 1: Contain the ARS and 2U instrument within 6U volume and mass limits • FR 3: Open instrument cover pointing away from the sun to avoid solar wind • FR 4: Tilt the CubeSat up to a max of 45° off the surface, optimal for dust collection • FR 6: Process data and run ARS algorithms



ARS Sun Testing

Location	Dark Room
Equipment	● Fully assembled CubeSat ● Power supply (5V) ● Flashlight ● PC
Data Out	● Sun vector
Requirements Verified	● FR 3: Open instrument cover pointing away from the sun to avoid solar wind ● FR 4: Tilt the CubeSat up to a max of 45° off the surface, optimal for dust collection ● FR 6: Process data and run ARS algorithms





Instrument Test Results

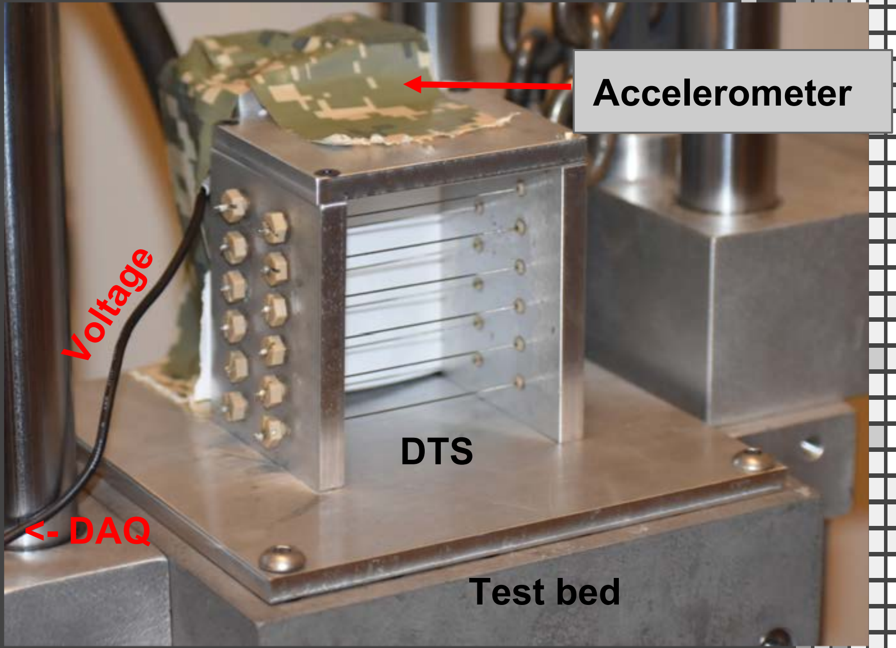
DTS Drop Test

Focusing on wire electrodes

Solidworks model predicts that the wire electrodes will survive a 10 m/s impact

Maximum achievable drop height was 127 cm, corresponding to a measured 4.7 m/s with Lansmont machine

- Unable to test a 10 m/s impact



DTS Drop Test Results

Maximum tested velocity: 4.7 m/s

All 12 wire electrodes remained intact and measurement planes were unaffected

M3 bolt threading weakened allowing structure to wiggle (shown below)

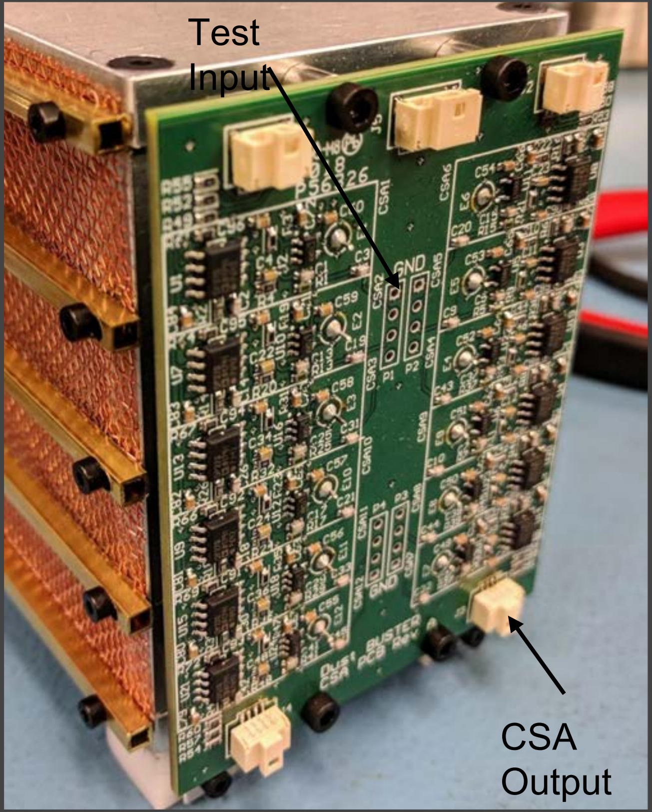
Consider bolt hole redesign

Requirement 2.5 not fully verified

CSA Verification

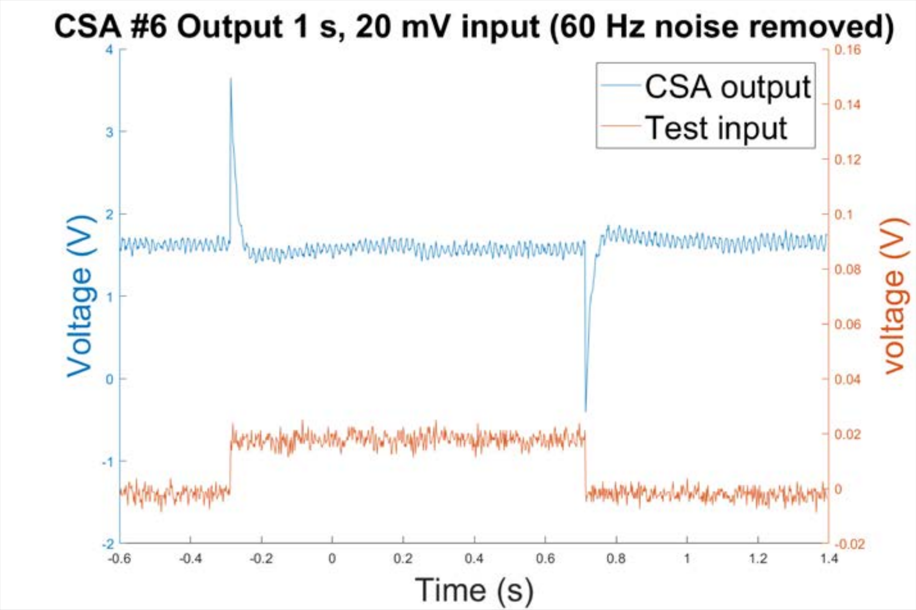
Charge Sensitive Amplifier PCB:

- No revisions needed
- CSAs have customer-accepted noise level and can amplify dust signals as expected
- 1 test board partially populated
- 3 final boards fully populated/verified



CSA Verification Result

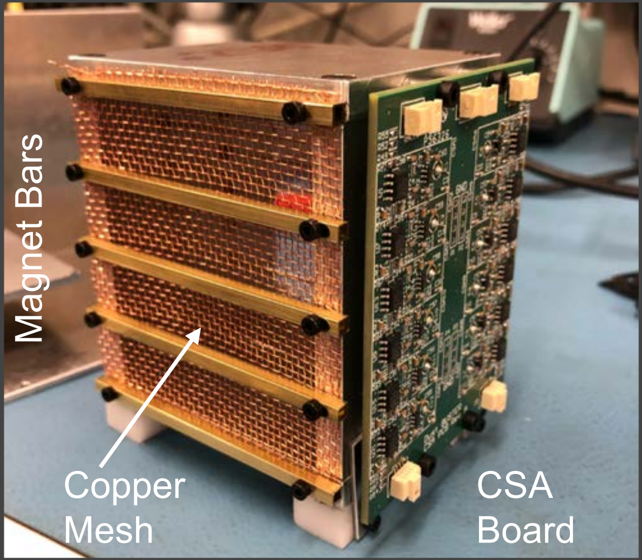
Compare output to expected behavior of ideal circuit



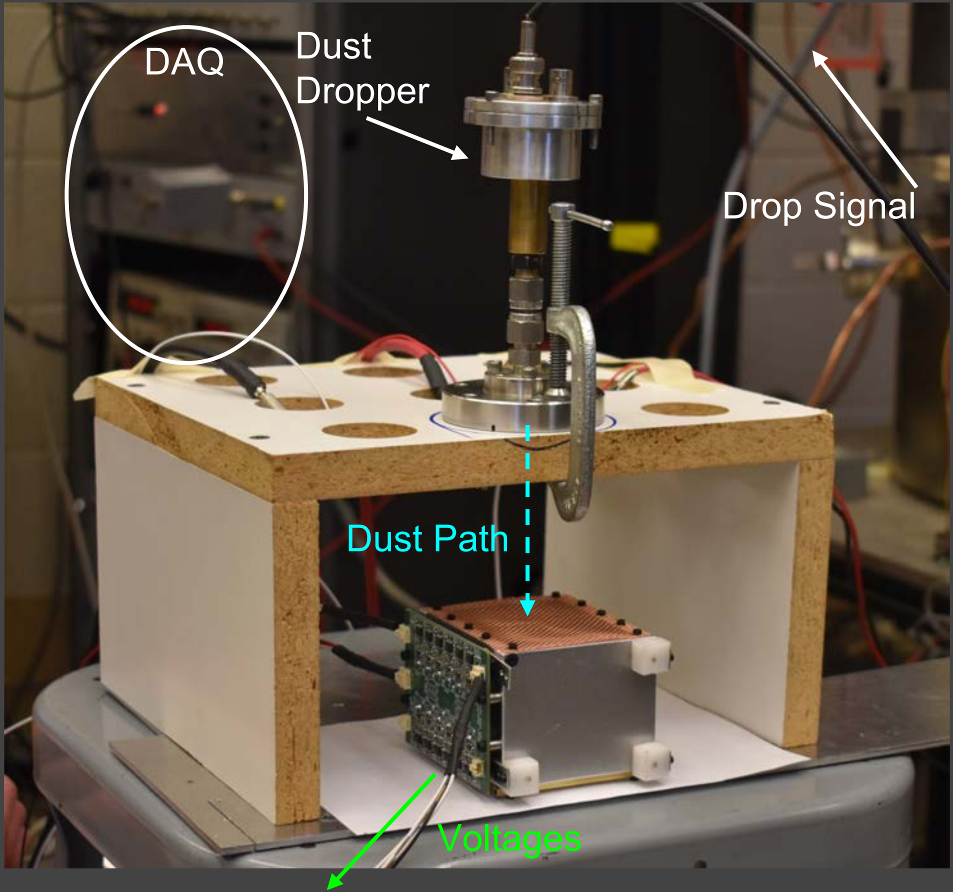
	Ideal Op-amp Model (V)	Result (V)
Average	1.61	1.61
Positive Pulse Magnitude	2.00	2.04
Negative Pulse Magnitude	2.00	2.02

Requirement 5.1 Verified:
The instrument circuit shall implement a charge sensitive amplifier for each electrode.

Dust Trajectory Sensor (DTS) Unit Test

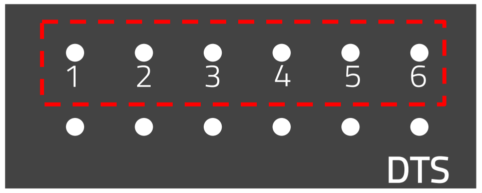


Fully Constructed DTS Unit



DTS Charge Test Results

Test Setup:



Due to hardware limitations only 6 channels can be read

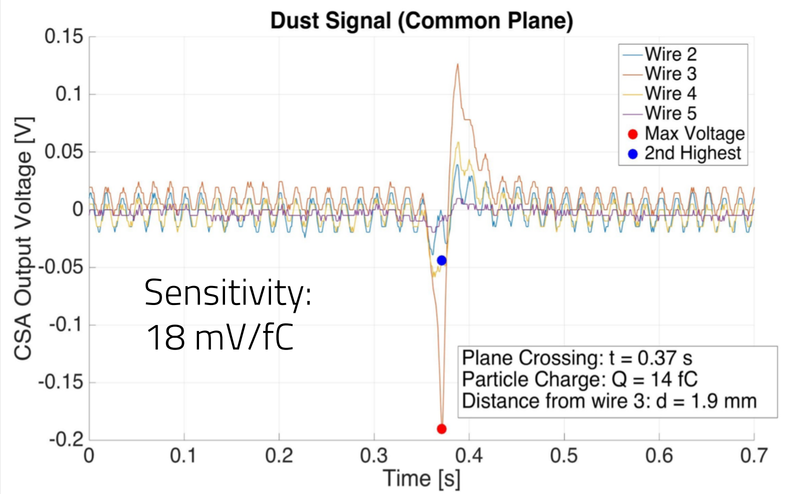
Expected Range (from customer):

1-150 fC

Experimental Range:

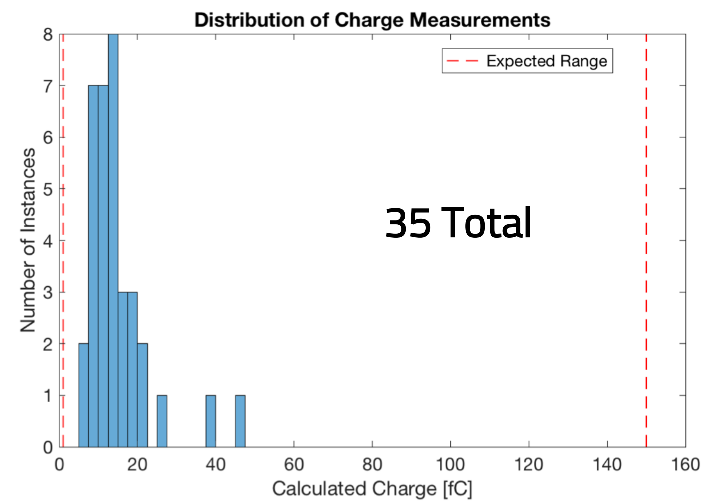
5-40 fC

DTS can successfully detect dust event, measure charge, and calculate z-coordinate of plane crossing



Sensitivity:
18 mV/fC

Plane Crossing: t = 0.37 s
Particle Charge: Q = 14 fC
Distance from wire 3: d = 1.9 mm



35 Total

DTS Velocity Test Result

7 total successful velocity events

Measure time difference between plane crossing

Expected Range (from customer):

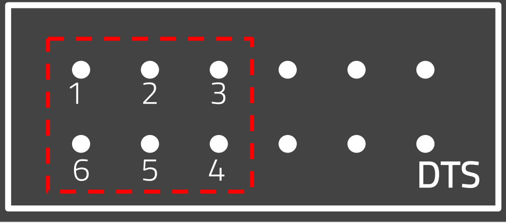
1 - 2 m/s

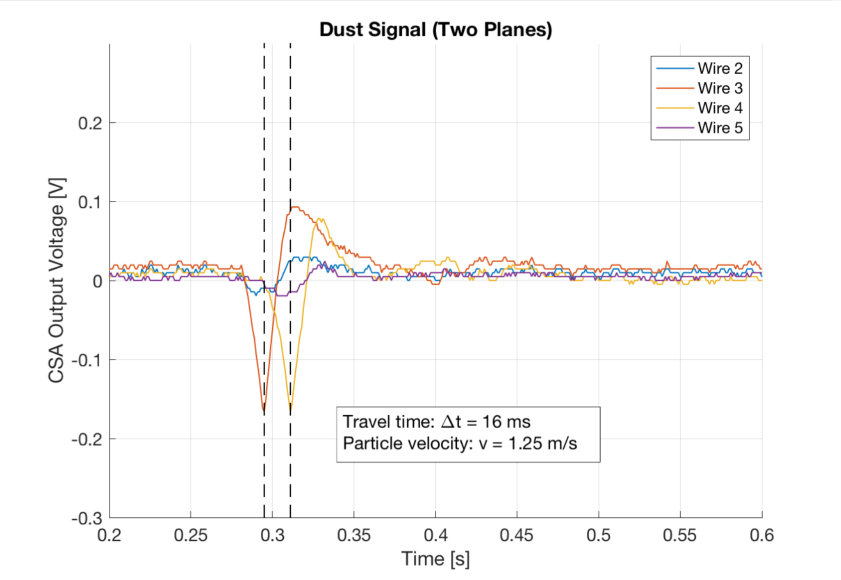
Experimental Range:

0.80 - 1.25 m/s

DTS can accurately measure velocity of the dust particle around range requested by the customer

Test Setup:





Travel time: Δt = 16 ms
Particle velocity: v = 1.25 m/s

Embedded System Status

- Microcontroller PCB: Complete
  - No revisions needed
  - Can flash code and debug execution
  - Protection circuits work as designed
  - 2 test boards partially populated
  - 1 final board fully populated/verified
- Real-time Software: In Progress
  - Redesigning architecture for simulated ADC data to test rest of software
- Software/Hardware Integration: Incomplete

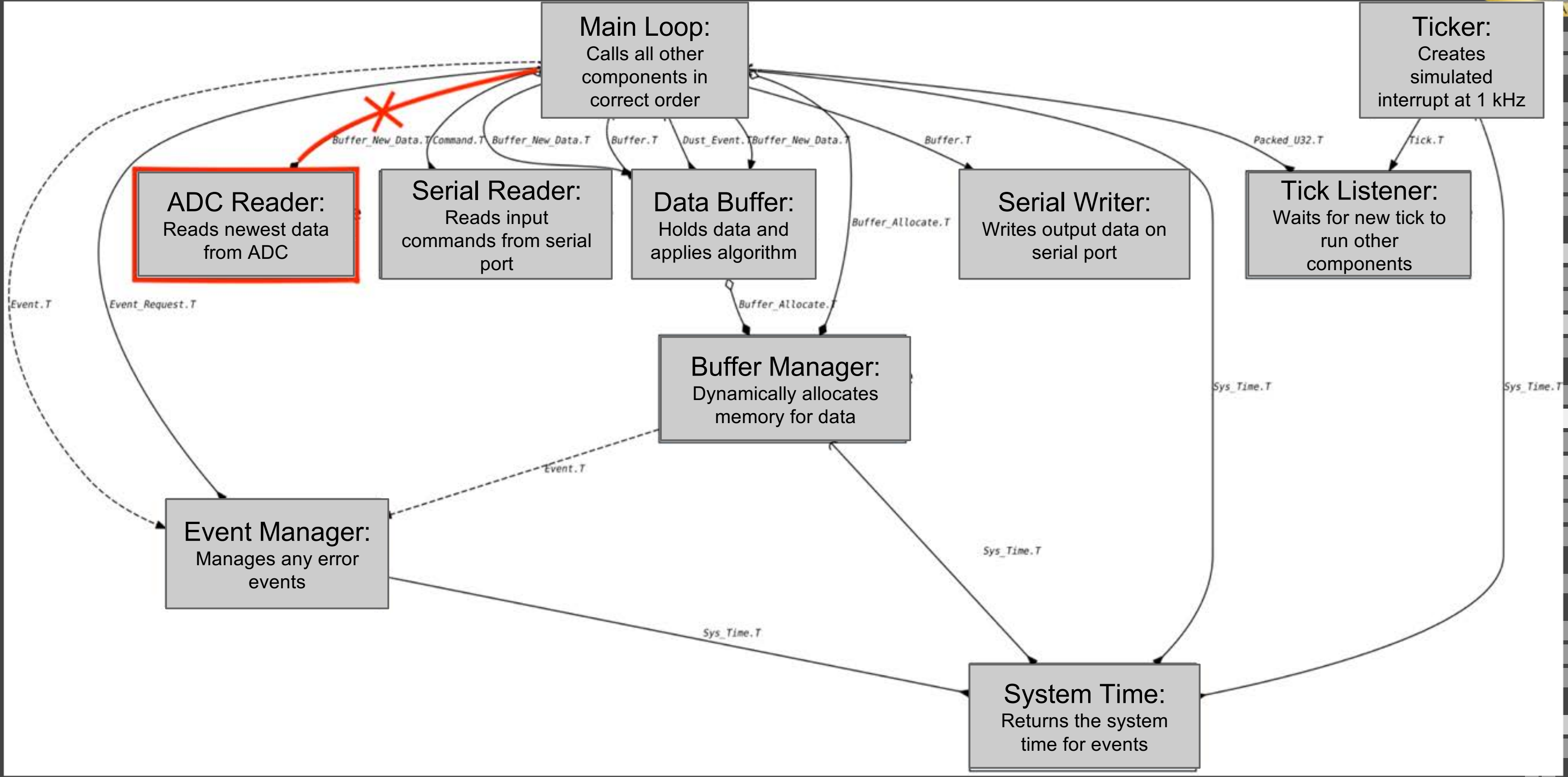
Embedded System Design Rationale

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

6.3 The instrument software shall continuously analyze data in order to detect all dust events.

- Custom design chosen so that microcontroller peripherals could handle fast sampling of 24 integrated ADC channels without needing software control
  - Required adding microcontroller ADC pin protection
- LASP Adamant flight software framework chosen to alleviate real-time software architecture difficulty

Software System Diagram



Main Loop:
Calls all other components in correct order

Ticker:
Creates simulated interrupt at 1 kHz

ADC Reader:
Reads newest data from ADC

Serial Reader:
Reads input commands from serial port

Data Buffer:
Holds data and applies algorithm

Serial Writer:
Writes output data on serial port

Tick Listener:
Waits for new tick to run other components

Buffer Manager:
Dynamically allocates memory for data

Event Manager:
Manages any error events

System Time:
Returns the system time for events

Instrument Remaining Work

- Software/Hardware Integration
    - Drivers need to be written to configure MCU timer, ADCs, and DMA for 1 kHz sampling and data manipulation
    - Required MCU configuration is well-known
    - Interface from MCU peripherals to software needs to be implemented
- Simulated dust event data will be used to attempt to trigger the algorithm and print results to text file
    - Will show ability of software to detect dust, output data, and respond to input user commands
    - Will verify that system can operate within 1 kHz frequency

Instrument Conclusions

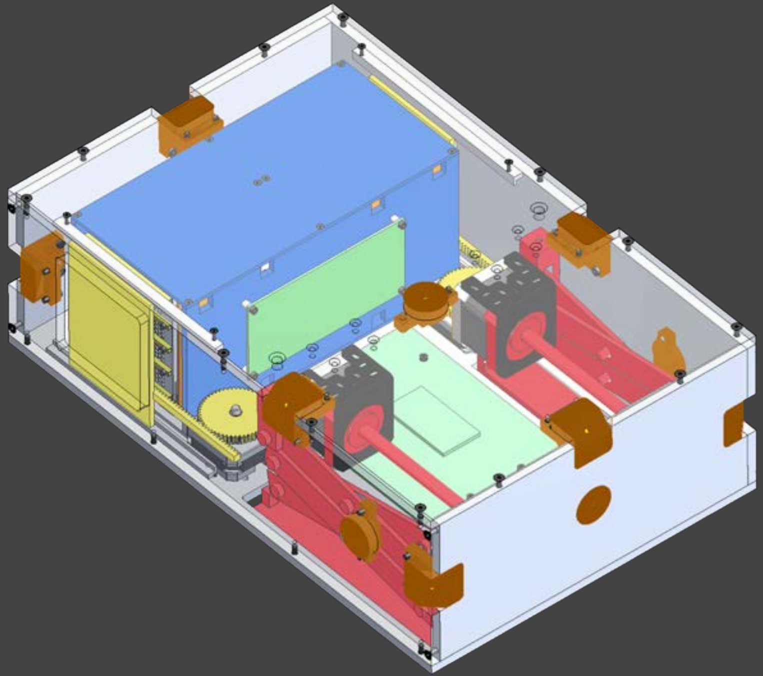
Requirement	Level 1 Success	Level 2 Success	Level 3 Success
Hardware	Detects dust Operates in vacuum	10 m/s impact	-
Software	External trigger Send data over serial Post processing algorithm	Self triggering algorithm	Uncertainty in Q, v, m

Requirements for stand-alone embedded system were over-ambitious and tightly-coupled

Team lacked sufficient time and expertise to handle all aspects of the design

Should have looked for a capable COTS hardware solution in order to focus on software design needs

Adamant framework limited the ability for other team members to help



ARS Test Results

Mass and Volume Requirements

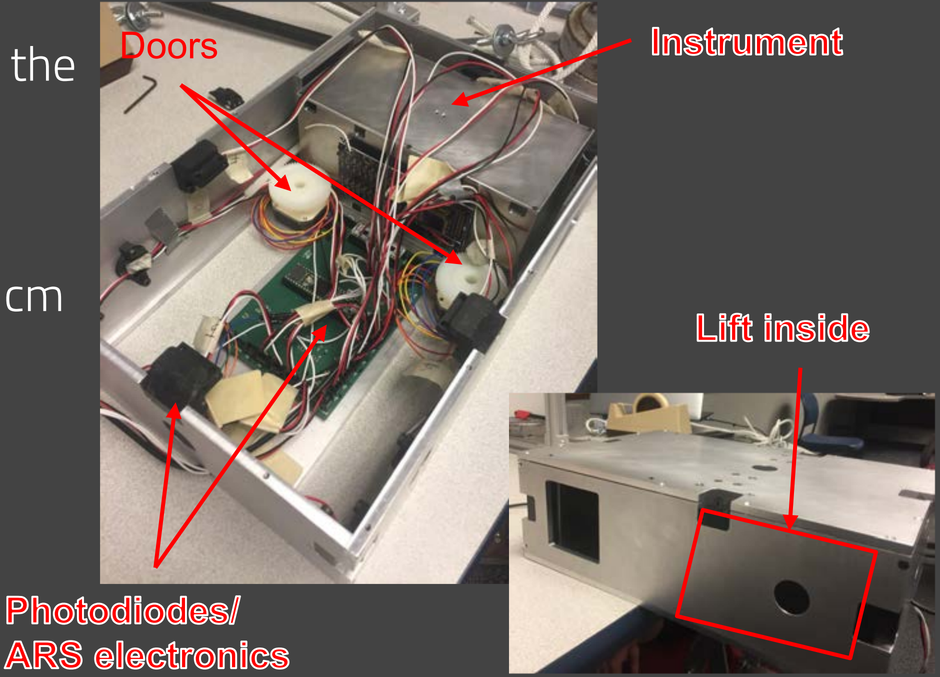
FR 1 The CubeSat model shall contain the ARS and 2U instrument within 6U volume and mass limits.

All components mounted inside the CubeSat shell and closed

Final mass of 8.41 kg

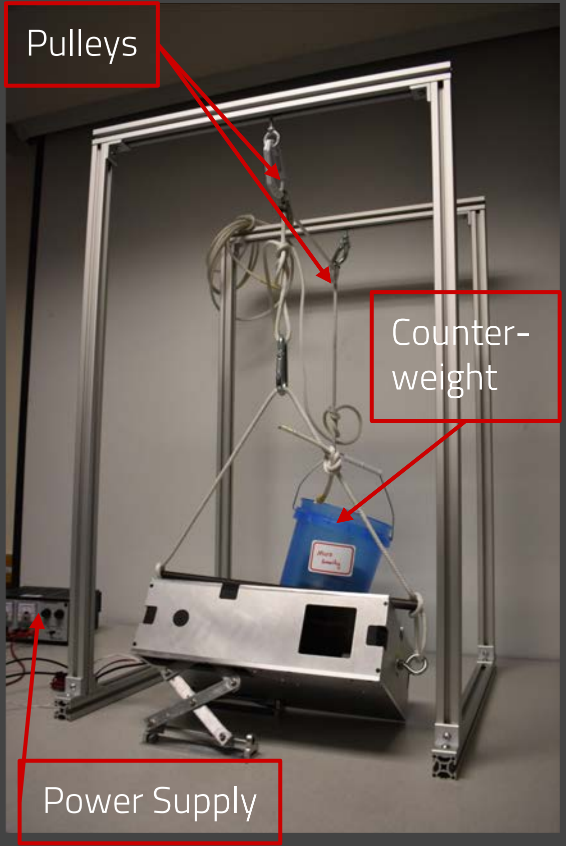
< 12 kg max

Dimensions: 23.9 x 36.6 x 11. 6 cm



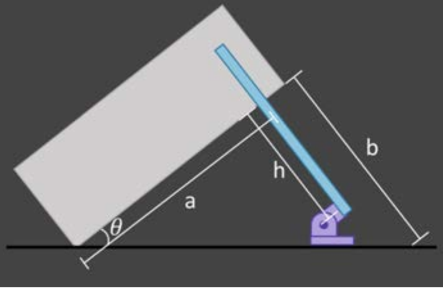
Tilt Test Setup

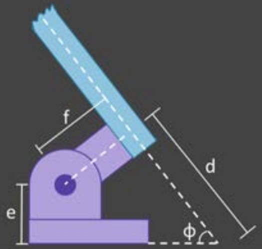
- Used a rope and pulley system
  - Rope connects CubeSat to counterweight through pulley system
    - Attaches to center of mass of CubeSat
- Power is provided using external power supply
- Measure angles using accelerometer and protractor
- Command teensy to step motors by a predetermined amount from model
  - Open loop by manual commanding
  - Closed loop using accelerometer feedback

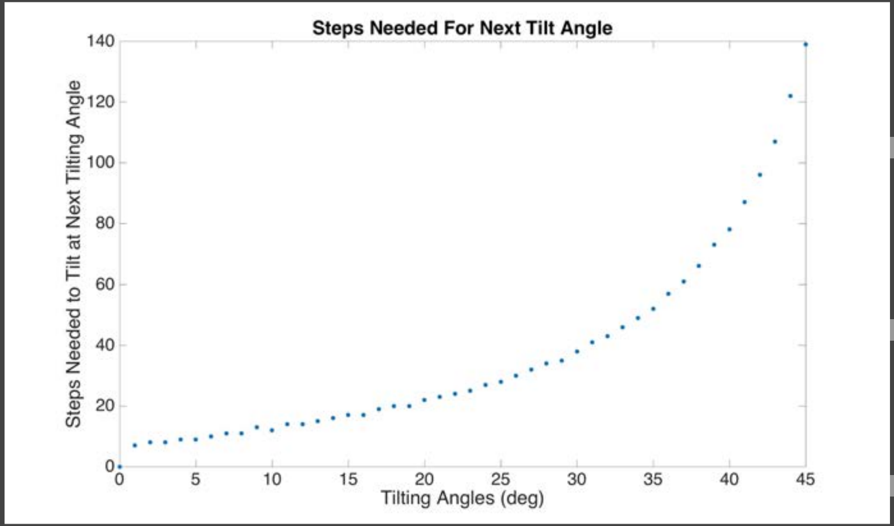


Tilting Model

- Tilting model calculates tilt angle based off of geometry in CubeSat
    - Takes into account “foot” and internal portion of the leg
- Initial tests showed some deviations from our model, especially at early tilt angles
    - Were a result of manufacturing tolerance stack up and test setup problems







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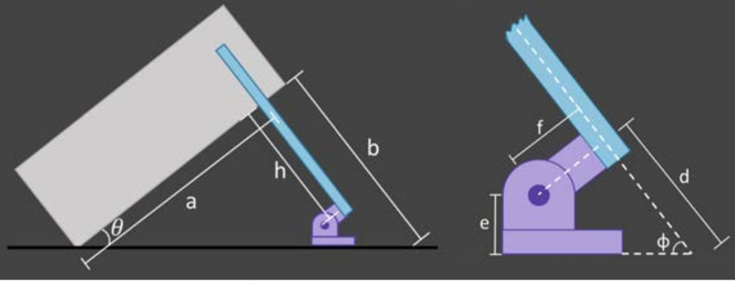
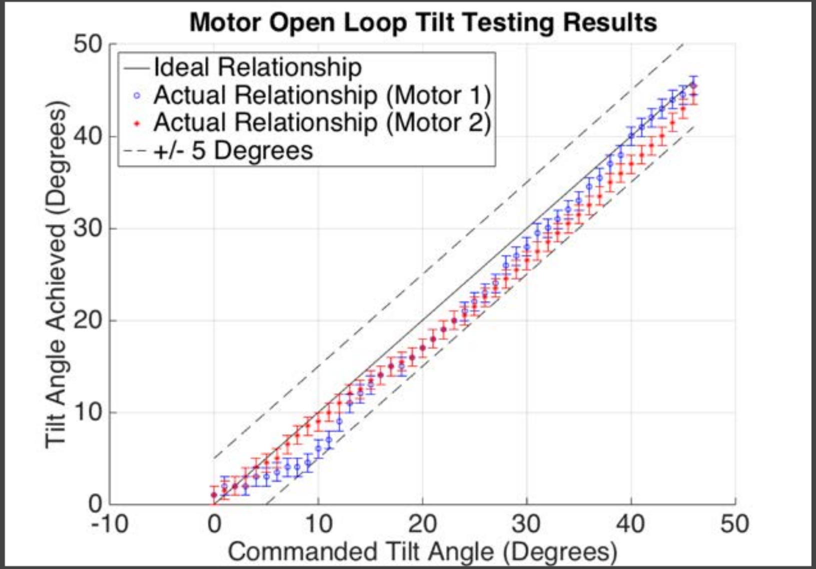


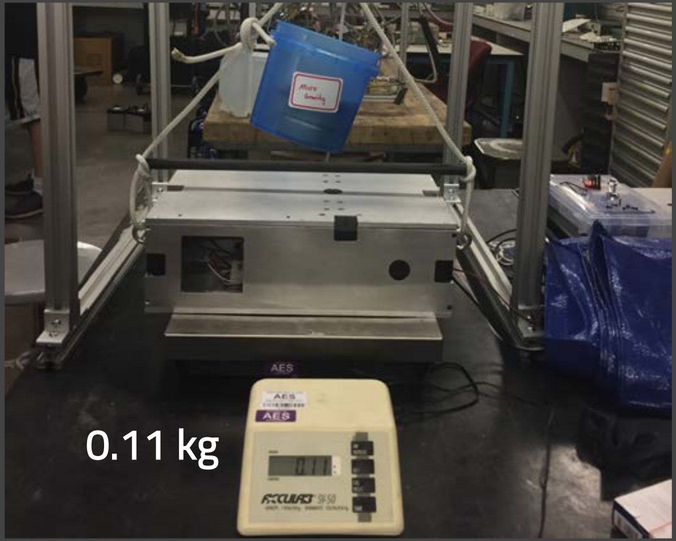


Tilting Test Problems

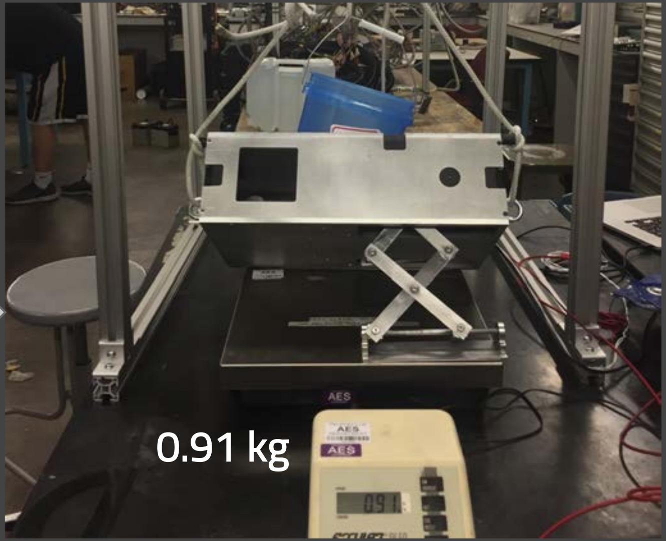
Friction in pulley made it difficult to consistently represent microgravity environment

- As tilt angle increased, mass that the scale was reading increased from 0.11 kg to 0.91 kg

Had to further reduce weight of CubeSat as it was tilting



Tilt 30°



Tilting Test Problems

- Tolerance stack up led to issues in leg deployment
  - Leg platform jammed against leg opening
    - Opening was shifted 0.07" towards CubeSat edge
    - Legs were short 0.05"
    - Only gave ourselves 0.1" margin
  - Also lead to increased friction in scissor lift
- Lead to missed steps during tilting, especially at low tilt angles
- Ultimately cannot verify that we can tilt the mass that we designed for

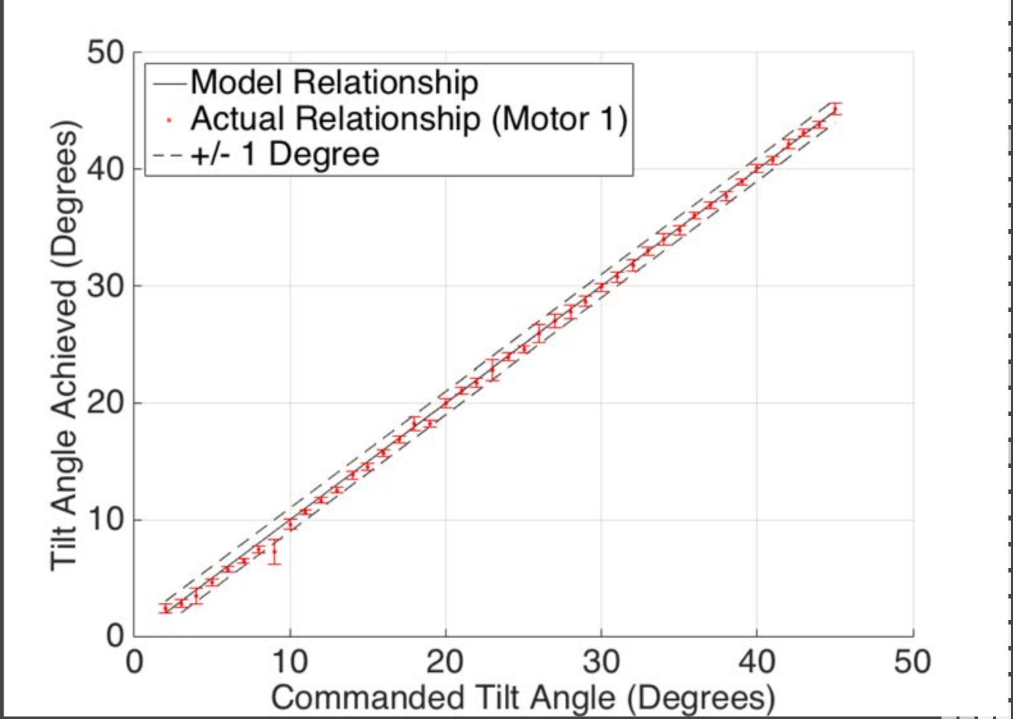
Requirement 4.122 Incomplete: The actuators shall be able to tilt a mass equal to 100g, with a 20g resolution, under earth's gravity field.

Closed-Loop Tilting Results

Meets third level of success (1° increments w/ 1° accuracy)

Closed loop control improved tilting precision and helped deal with missed steps issue

Only have data for one lift due to a motor failure



Requirement 4.121 Verified: The actuators shall be able to tilt the CubeSat in 1 degree increments with an accuracy of +/- 0.5 degrees

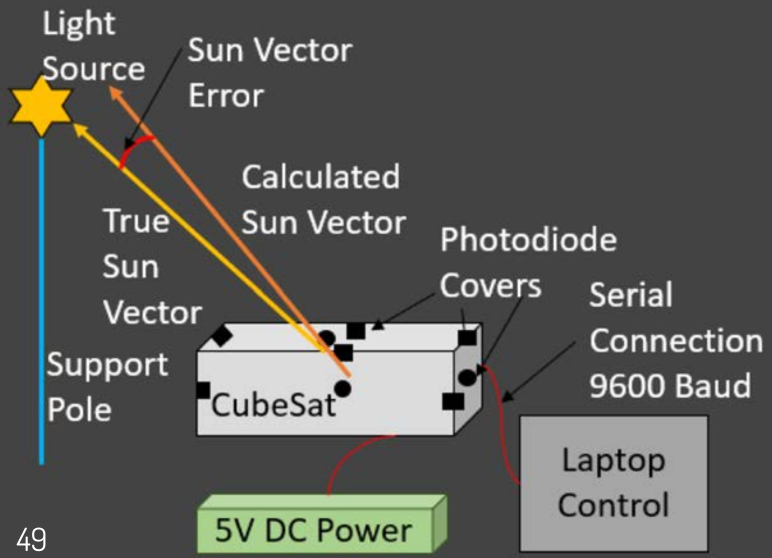
Tilting Test Conclusions

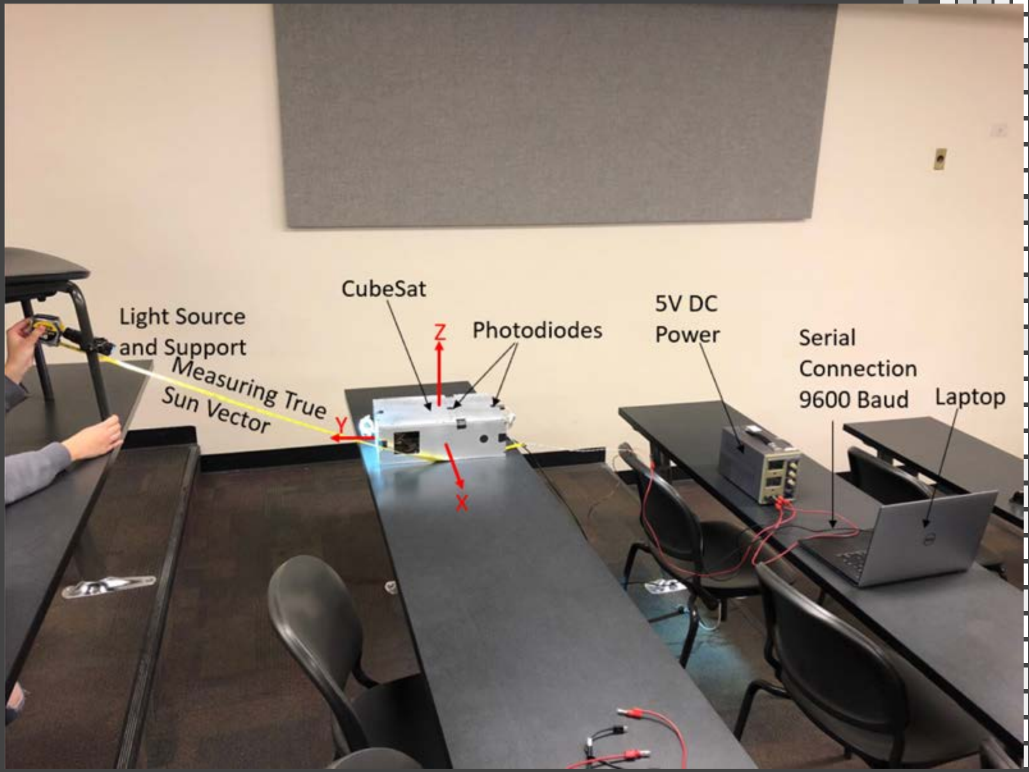
Requirement	Level 1 Success	Level 2 Success	Level 3 Success
Tilting Accuracy	Tilt CubeSat model up to 45 degrees on a flat surface	Open loop autonomous tilt with 5° accuracy	Closed loop tilt with 1° accuracy

- System can meet tilting requirements
    - Can’t verify it can meet mass tilting requirement
- Should have taken more care in manufacturing
    - Or potentially left time to re-manufacture parts
- Attempt to find a better way to represent a microgravity environment
    - Rope/pulley with lower friction
    - Different testing method
- Potentially change where torque is being applied in the scissor lift

Sun Sensing Characterization Test Setup

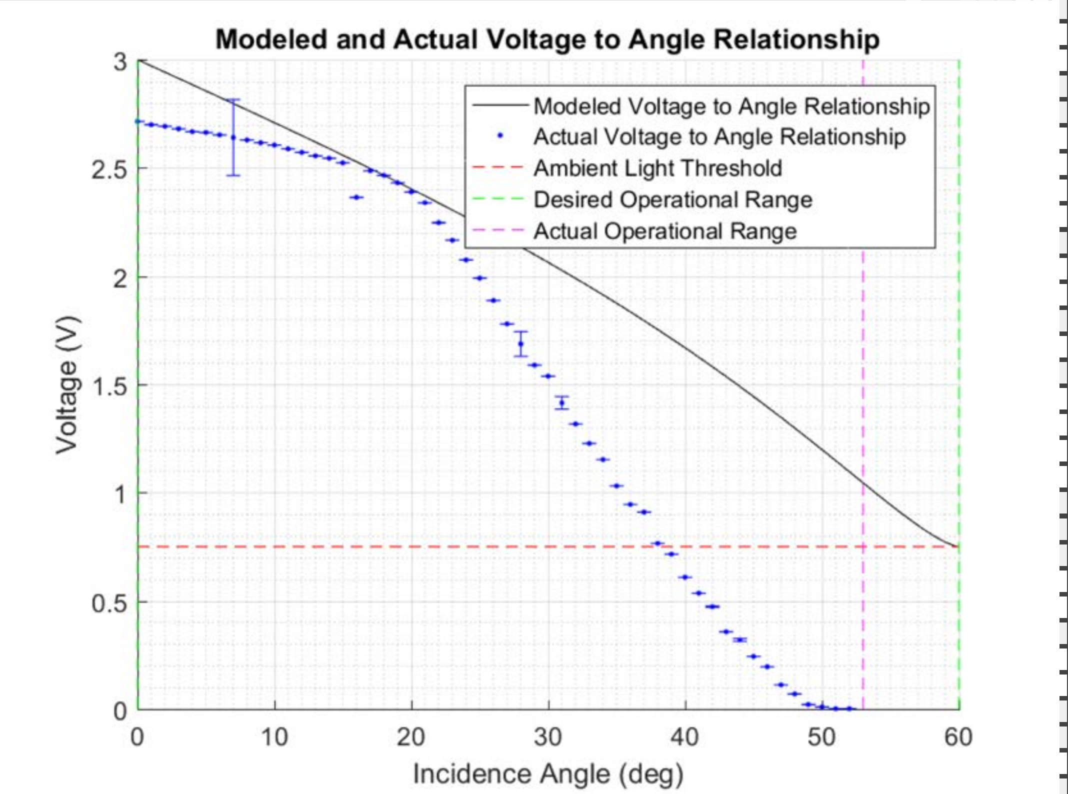
True sun vector measured in X,Y,Z CubeSat Body Axes Compared to computed sun vector





Angle to Voltage Relationship Errors

- Photodiode roll-off was greater than expected based on data sheet, using up margin for ambient light
  - Modeled vs actual slope
  - Data sheet values used in models
- 3D printed covers required modifications to reach 60° FOV
  - Cover calibration data (with error bars)

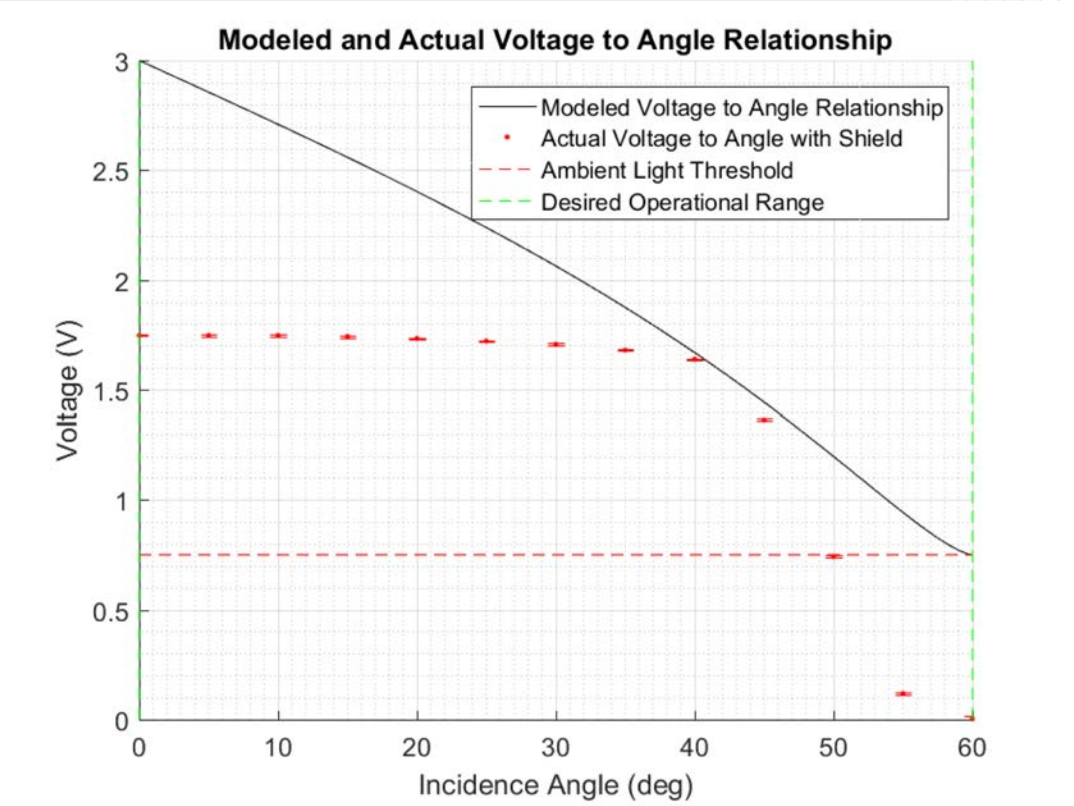


Angle to Voltage Relationship Errors

Diode in MCU pin protection circuit clipped voltages lower than desired

- Vector calibration data (with error bars)

Low resolution at low incidence angles

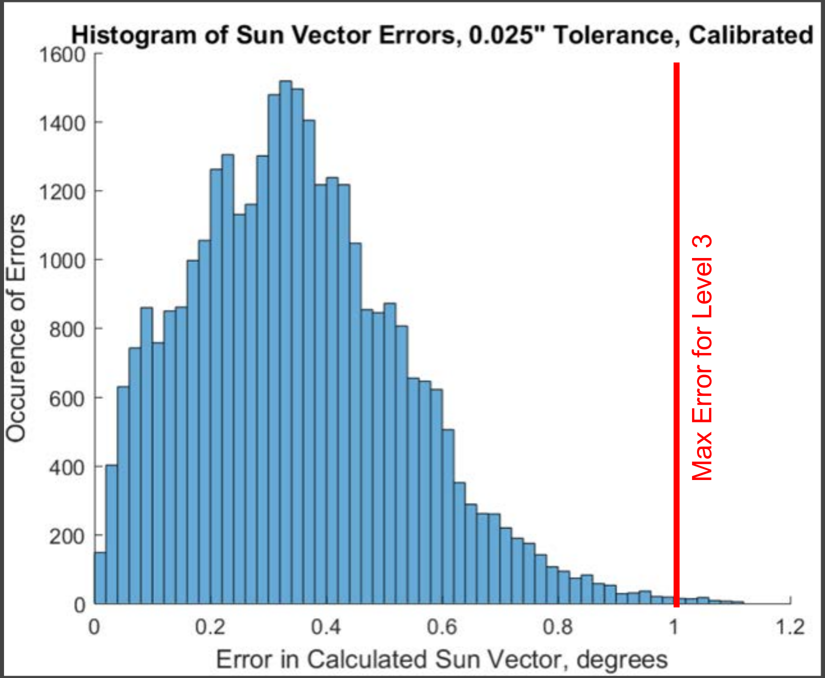

Modeled and Actual Voltage to Angle Relationship

Sun Sensing Characterization Results

Purpose: Verify the sun vector 1° accuracy requirement

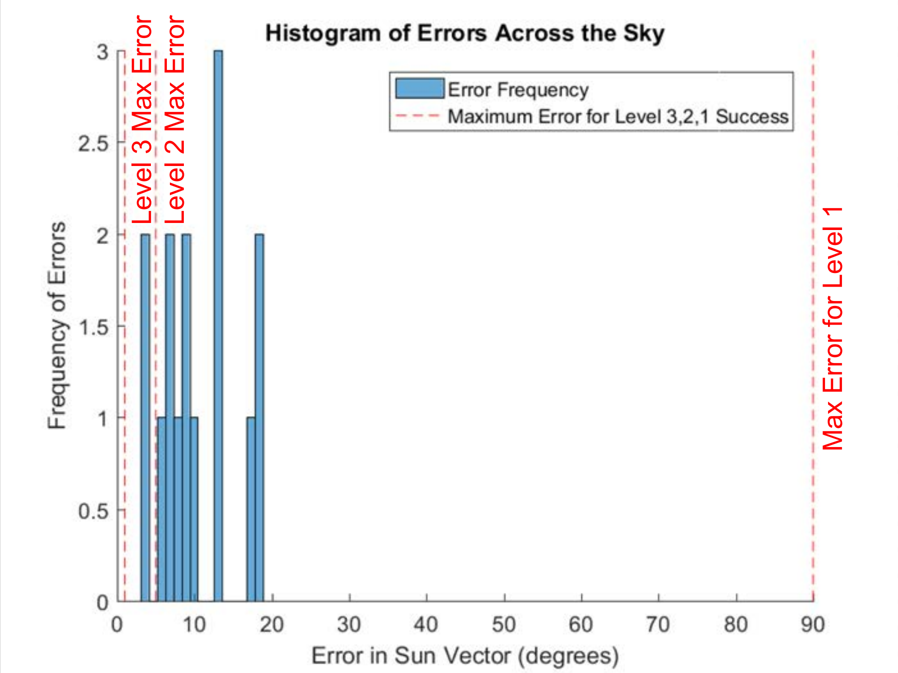
Original Modeled Errors

Designed for level 3 (1°)



Tested Errors

Achieved level 1 success (90°)

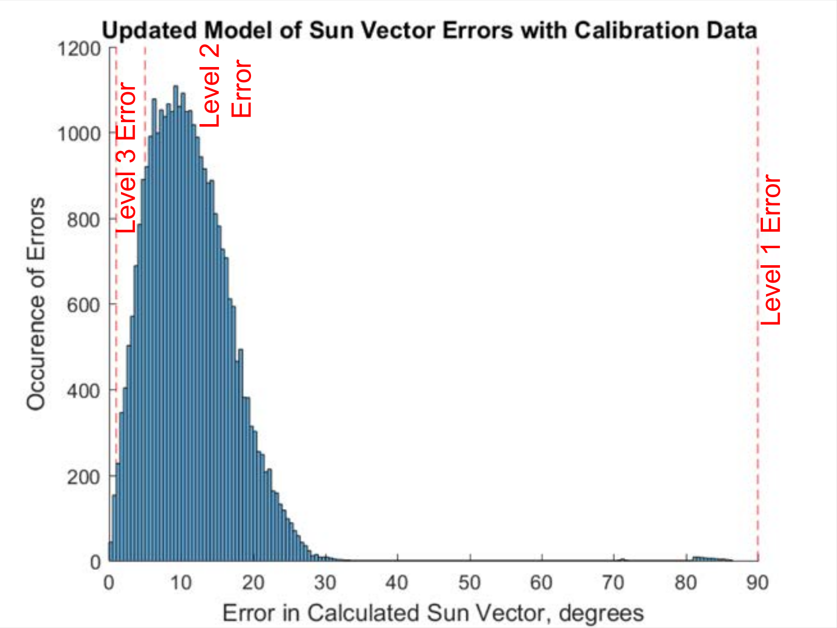


Sun Sensing Characterization Results

Purpose: Verify the sun vector 1° accuracy requirement

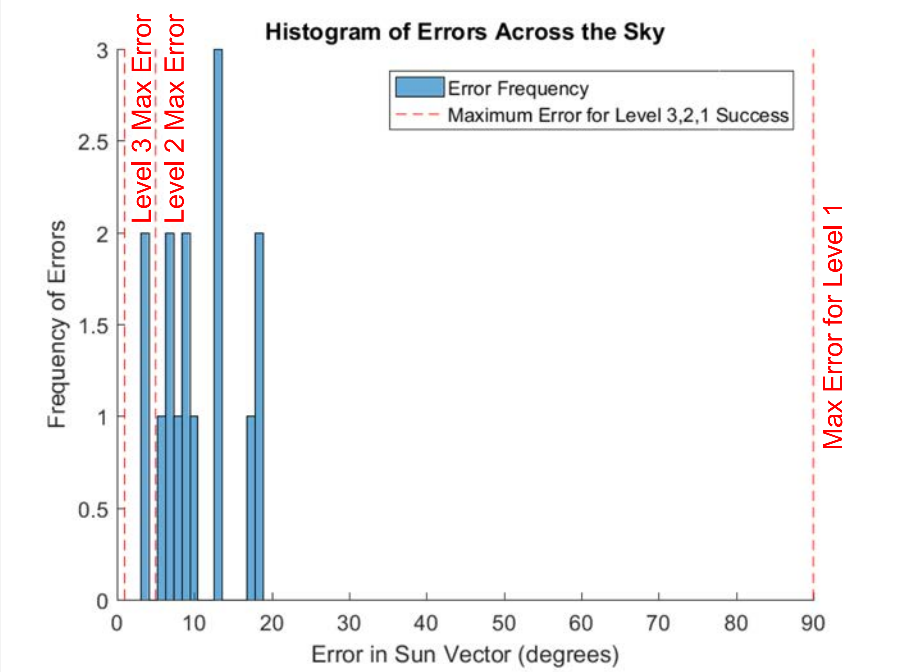
Updated Modeled Errors

Added Calibration Data to Model



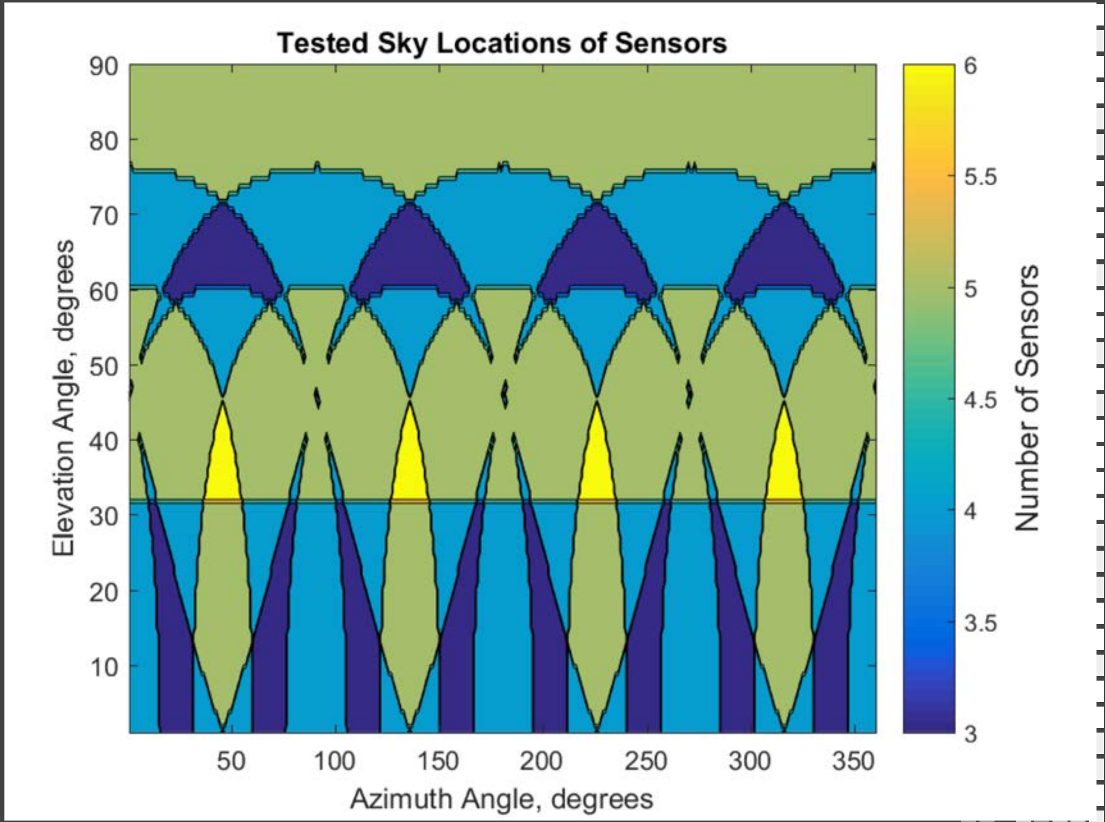
Tested Errors

Achieved level 1 success (90°)



Full Sky Coverage Model

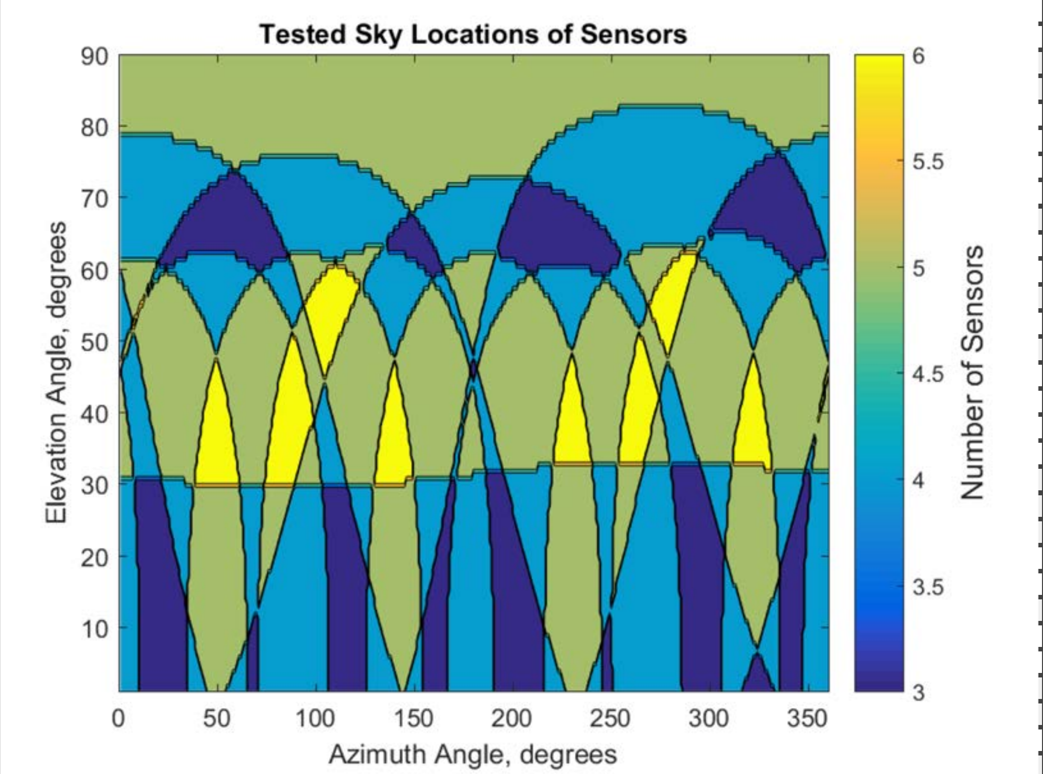
- Designed for at least 3 photodiodes on each part of the sky with significant margin
    - All locations had at least 3 sensors



Full Sky Coverage Requirement Verification

- Component test calibration results
  - Known alignment of photodiodes and fields-of-view
- Geometry used to derive true sky coverage map

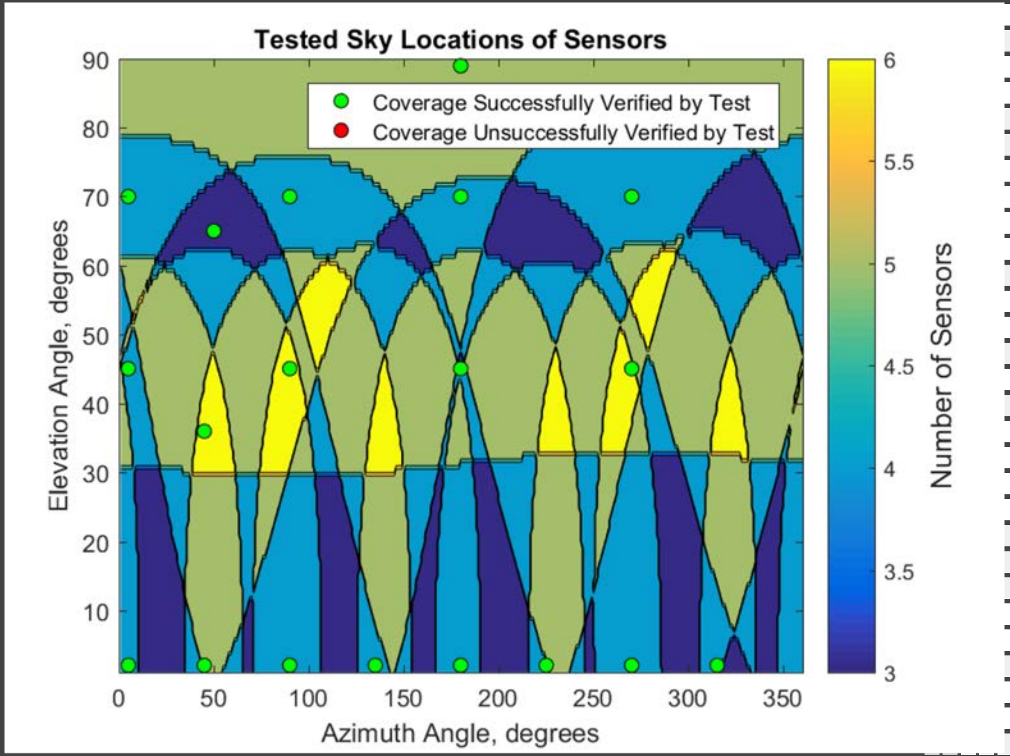
Full Sky Coverage Requirement Verified by Analysis



Full Sky Coverage Requirement Verification

- Component test calibration results
  - Known alignment of photodiodes and Fields-Of-View
- Test locations based on unique combinations of sensors in modeled coverage map

Full Sky Coverage Requirement Verified by Analysis and Test



Sun Sensing Conclusions

Requirement	Level 1 Success	Level 2 Success	Level 3 Success
Sun Vector Accuracy	90°	5°	1°
Full Sky Coverage	Verified	-	-

Small errors in voltage to angle conversion propagated to large errors in sun vector

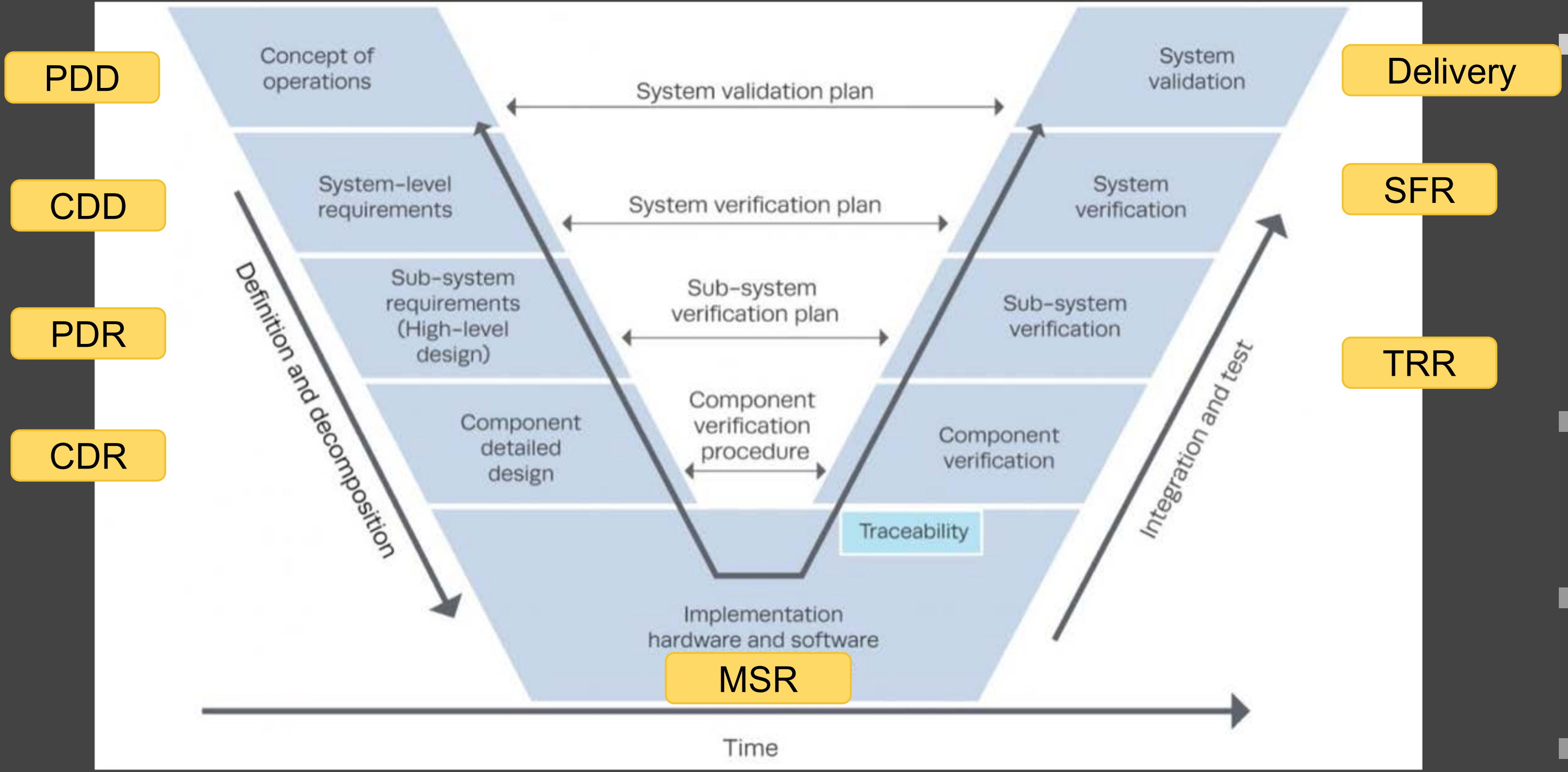
Calibrations were extremely valuable to get system working, but took more effort than expected

Filters effectively reduced noise

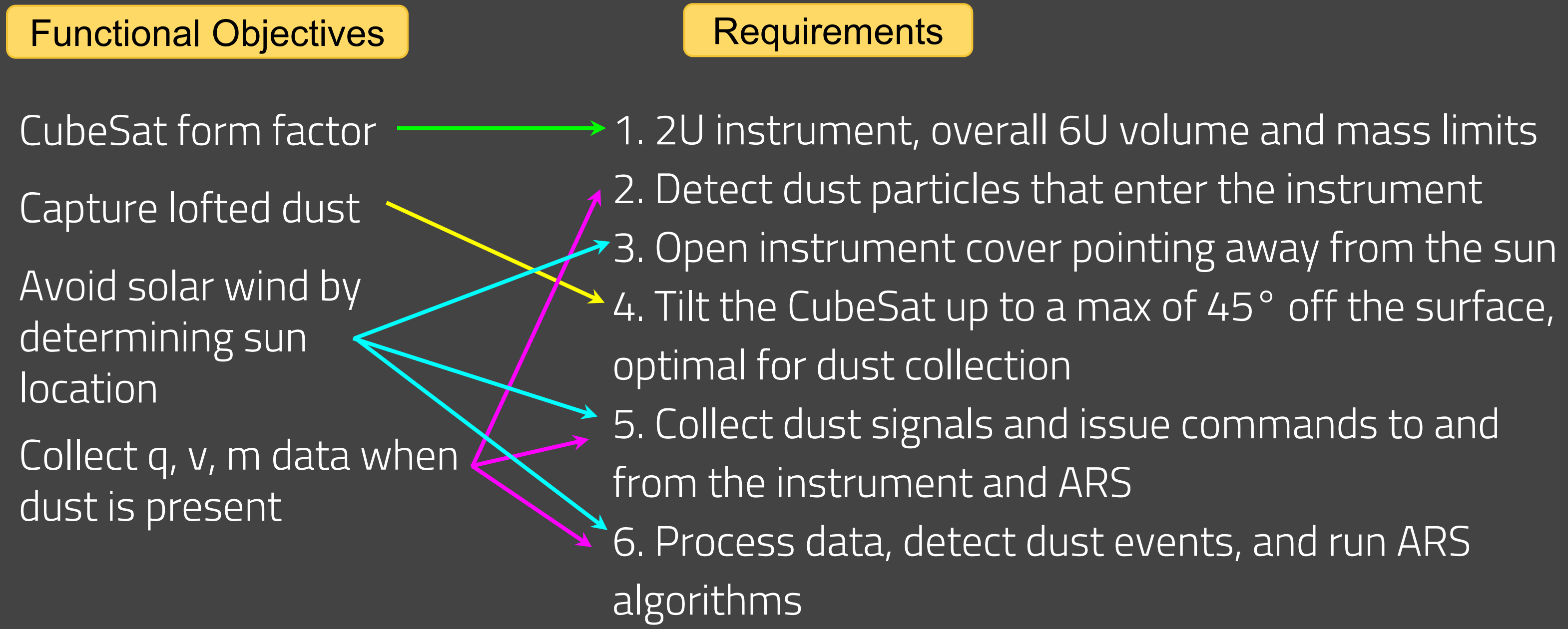
Requirements needed more detail for testing environment and how much accuracy customer actually needed

Systems Engineering

Systems Engineering Process



Requirements Flow Down



Functional Objectives

CubeSat form factor

Capture lofted dust

Avoid solar wind by determining sun location

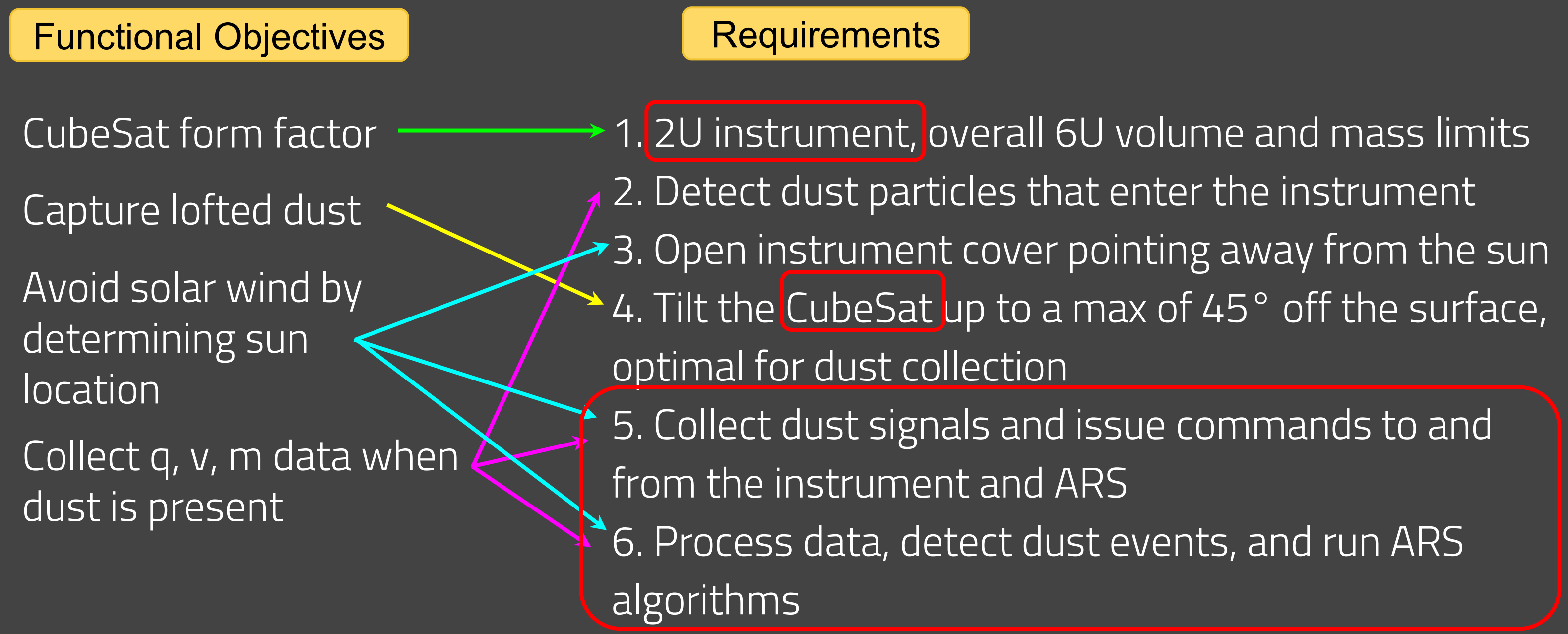
Collect q, v, m data when dust is present

Requirements

1. 2U instrument, overall 6U volume and mass limits
2. Detect dust particles that enter the instrument
3. Open instrument cover pointing away from the sun
4. Tilt the CubeSat up to a max of 45° off the surface, optimal for dust collection
5. Collect dust signals and issue commands to and from the instrument and ARS
6. Process data, detect dust events, and run ARS algorithms

Lessons Learned: Utilize more resources to understand the work necessitated by requirements and project scope from the beginning

Requirements Flow Down



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Key Trades

Mechanisms

Sun-Sensing

Instrument Electronics/Software

Should have given greater weight to:

- The difficulty of developing a new system from scratch (instrument and sun sensing)
  - Looked further into other COTS systems
- Stringency of manufacturing tolerances for a design (scissor lift and sun sensing)
- Team expertise and experience (all)
- Amount of resources the team can dedicate to the sub-system in time allotted (all)

Lessons Learned: Trade studies should heavily consider all factors in the implementation of a design, not just the design itself

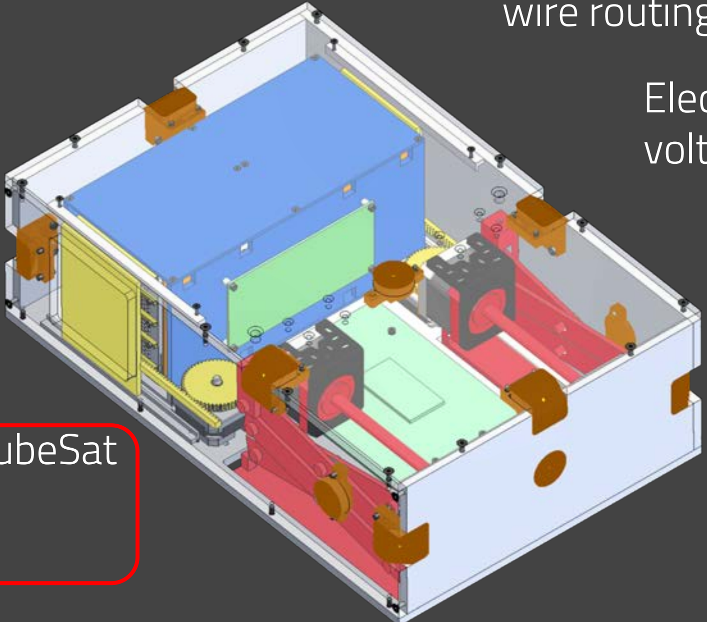
Interfaces

EMI and ESD precautions, electrical isolation

Software and hardware interaction

Mounting to test apparatus

Precision mounting in CubeSat body for mechanisms and photodiodes



Clearance and ports for connectors and wire routing

Electrical components and voltage/current levels

Clearance and lubrication for door and scissor lift

Combining tilting, sun sensing, and accelerometer software

Lessons Learned: Interface management saved time during integration, difficulties with datasheets, software, and mounting in real life vs CAD

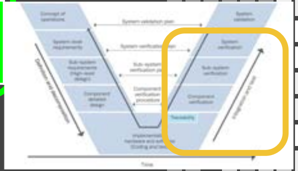
Risks in Retrospect

		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							
🟩	Low (1-3)	🟨	Moderate (4-9)	🟧	High (10-15)	🟥	Extreme (16-25)

Updated Risks

Risk	Description	Status	Total
INT-4	Limited instrument testing pre-vacuum	Tested DTS w/out vacuum first	4
INST-2	Don’t have past test data	Still true, but now have our own	5
ELEC-1	Need to remake PCB	No remakes for instrument	4
MECH-1	Mechanism mounting errors	Misalignment in scissor lift	12
ARS-1	Photodiode noise	Mitigated with filters	2
ARS-6	Inconsistencies in photodiode apertures	Calibrated and adjusted	8
ELEC-4	Noise from connections and EMI	Mitigated with circuit design	5
STRUCT-2	Wire electrode does not survive impact	Survived up to 4.7 m/s	3



System Integration and Testing Risks

Additional or Updated Risks:

- Learning curve for instrument software and Ada (updated)
  - LASP engineer helped mitigate software risk but had limited experience in hardware/software integration
- Hardware inconsistent with datasheets (new)
  - Did not catch differences in photodiodes and door motors until integrated/tested
- Test setup impacts results (new)
  - Limited ability to simulate microgravity

Lessons Learned: Anticipated risks were effectively mitigated; challenges arose from unforseen or underestimated risks

Project Management

Management Approach

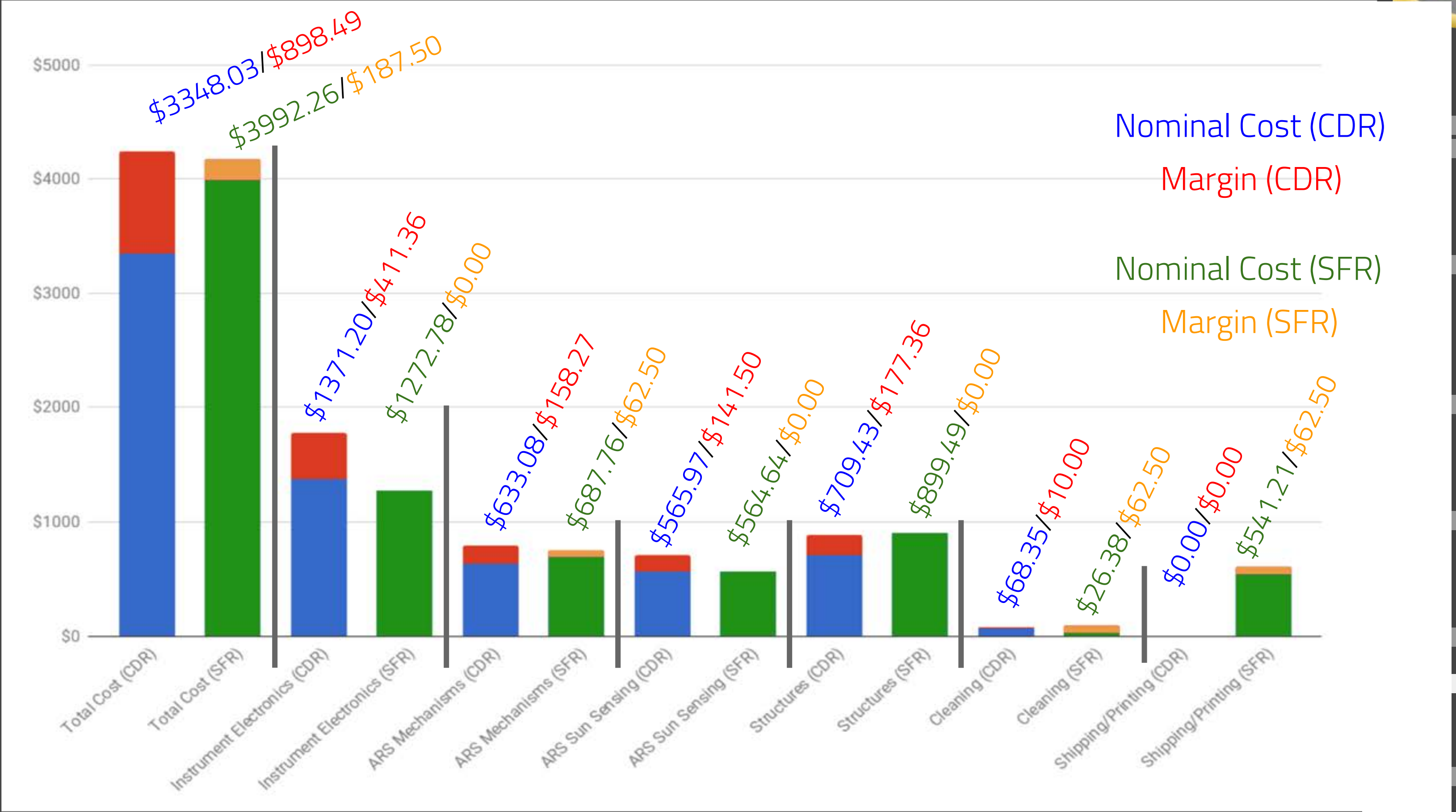
1st Semester	2nd Semester
Rigid and structured schedule	Dynamic and flexible schedule
Every team member worked on documentation	Split technical and documentation work (MSR, TRR, AIAA)
2 hour full team meetings	Brief status updates
Individual focused work	Group focused work (warm body approach)

Project Resources	Slack (Communication), Team Gantt (Scheduling), Google Drive (Documentation)

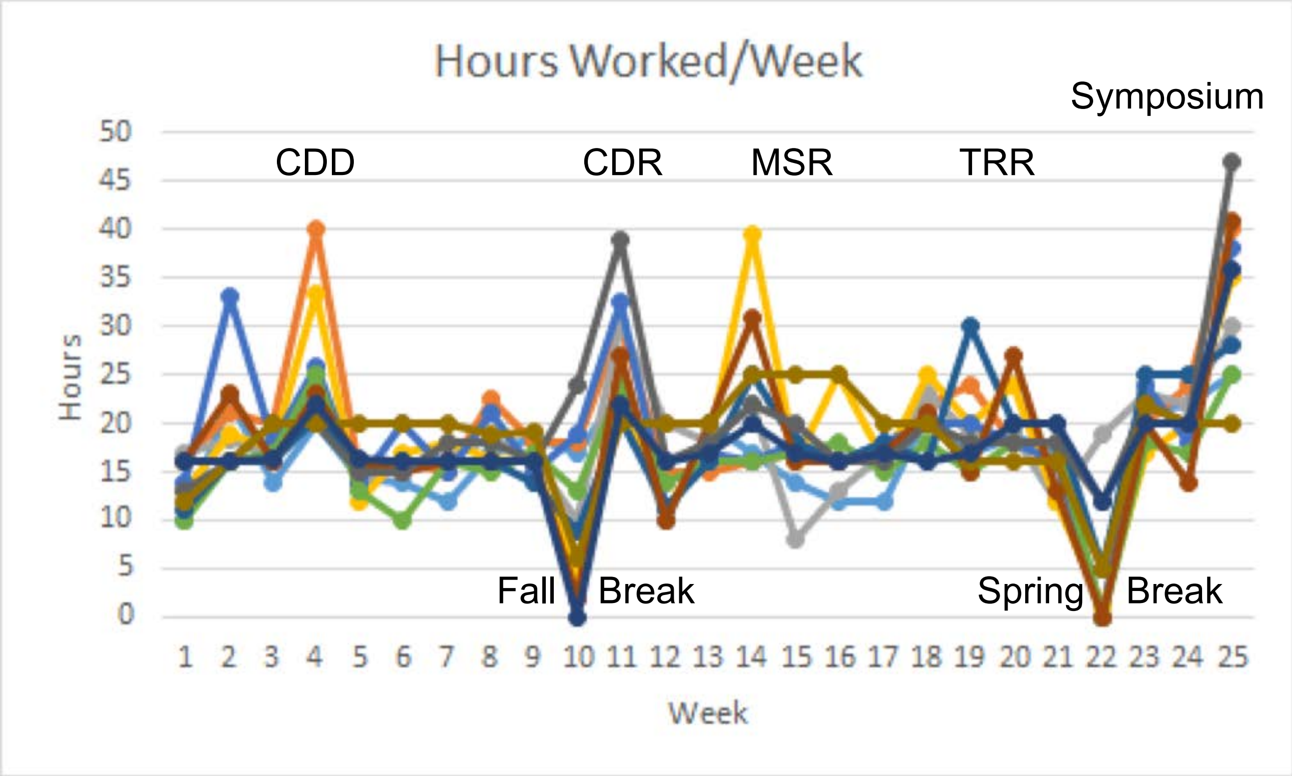
PM Lessons Learned

Successes	Challenges
Gantt Charts (1st semester)	Gantt Charts (2nd semester)
Increased customer communication	Didn’t understand complexity of certain components
Individual leadership	Misallocation of resources
Brief meetings	Overextended team

CDR Cost Plan vs. Final Budget



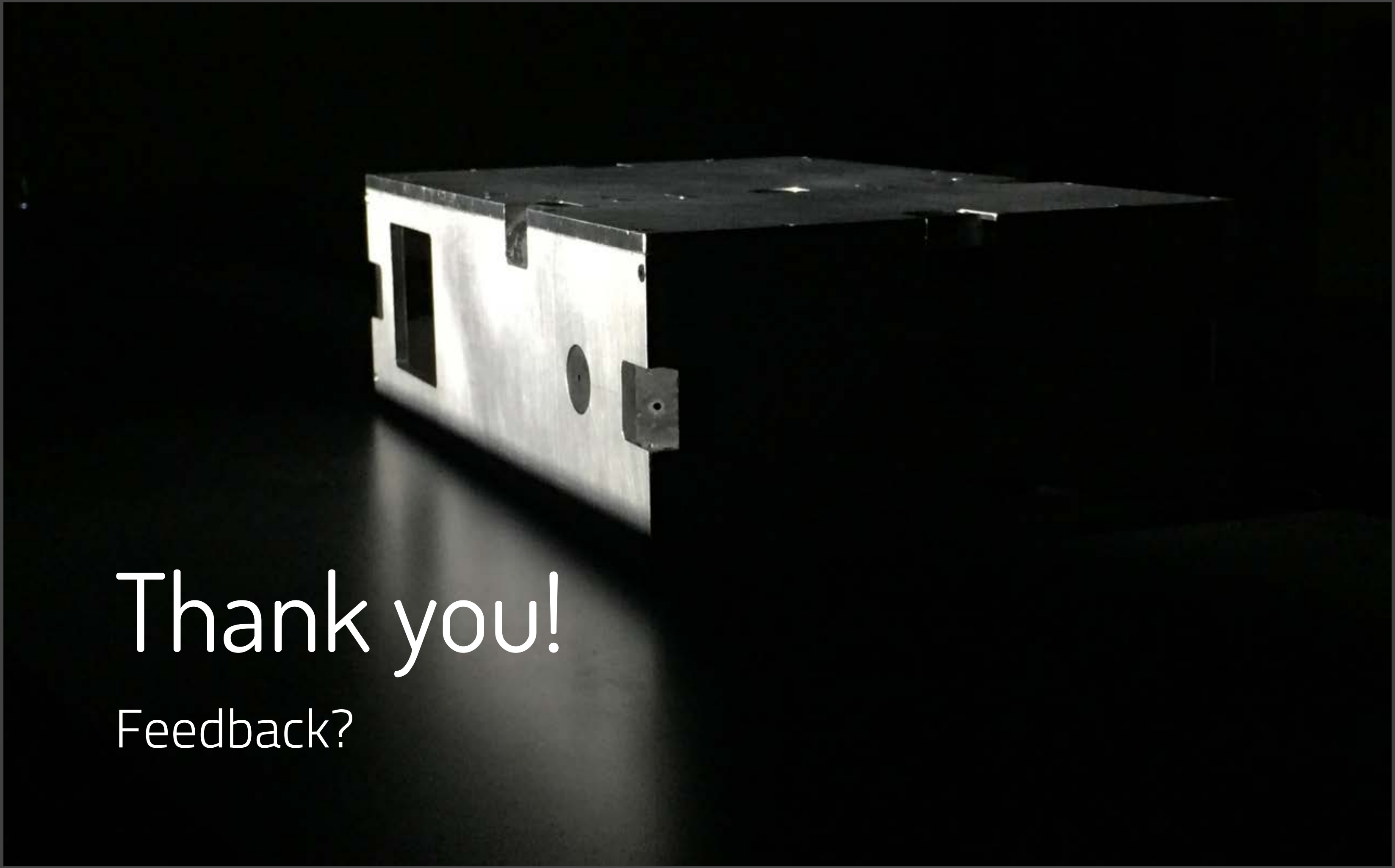
Time is $$$



Hours	5004
Rate	$31.25/hr
Labor	$156,375
Overhead	$312,750
Materials	$3,993
Total	$473,117

Acknowledgements

PAB - Specific technical advice
Dr. Clark - Advising with a broken arm
Dr. Wang & Dr. Sternovsky - Design, review, and testing
Kevin Dinkel - LASP framework
Joseph Samaniego-Evans - Instrument testing
Adrian Stang - Machining
Stu Tozer, BioServe - Cleaning
Dan Godrick - Accelerometer
Andrew Dahir - QB50 turn table and cleaning



Thank you!

Feedback?

Slide Directory

Backup Slides

Analog Electronics: Charge Sensitive Amplifier

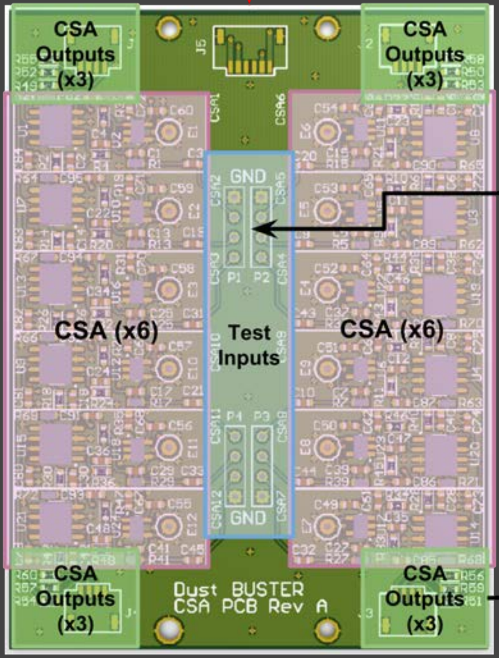
Verify our implementation of customer's design for a charge sensitive amplifier, Req 5.1, 5.11, 5.12

Purpose: Measure each CSA's amplification of a simulated dust event.

Facility: Electronics Lab

- Power supply (±5V & ±15V)
- Waveform generator
- Oscilloscope & probe
- ESD mat/straps
- Assembled CSA PCB

Measurement: voltage of the amplified signal (gain = 100)



1) Connect ±5.5 V and ±15 V

1) Set waveform generator to 1 ms, 20 mV pulse
2) Send to CSA test input

4) Measure outputs with an oscilloscope

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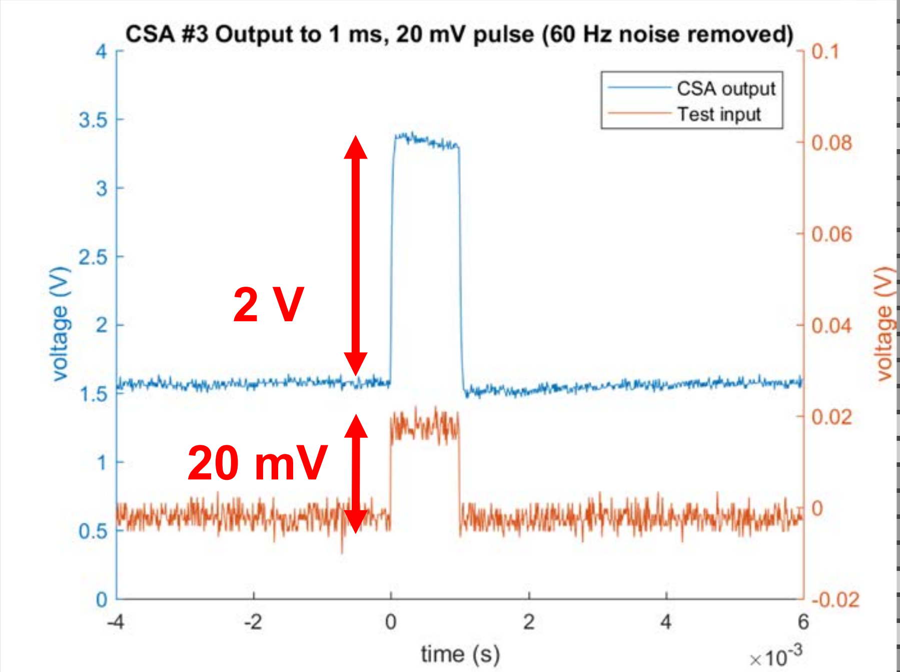


Impact Testing

Verify that Wire Electrodes can withstand 10 m/s impact (Req 2.5.1)

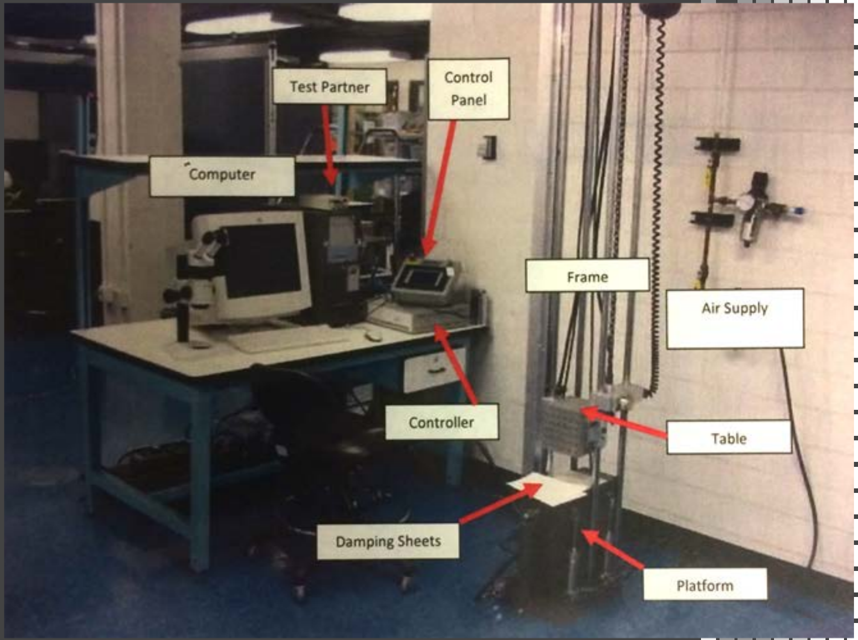
Purpose: Drop a DTS at successively larger impact velocities to characterize failure (when wire electrode becomes free to move)

Facility: Idea Forge

- Lansmont 15D Shock Test Machine
- One DTS unit
- Accelerometer

Procedure:

- Mount DTS to drop test table
- Raise table up to desired height and drop
- Visually inspect wire electrodes for broken or freely moving wires
- Drop again at new height



Impact Testing

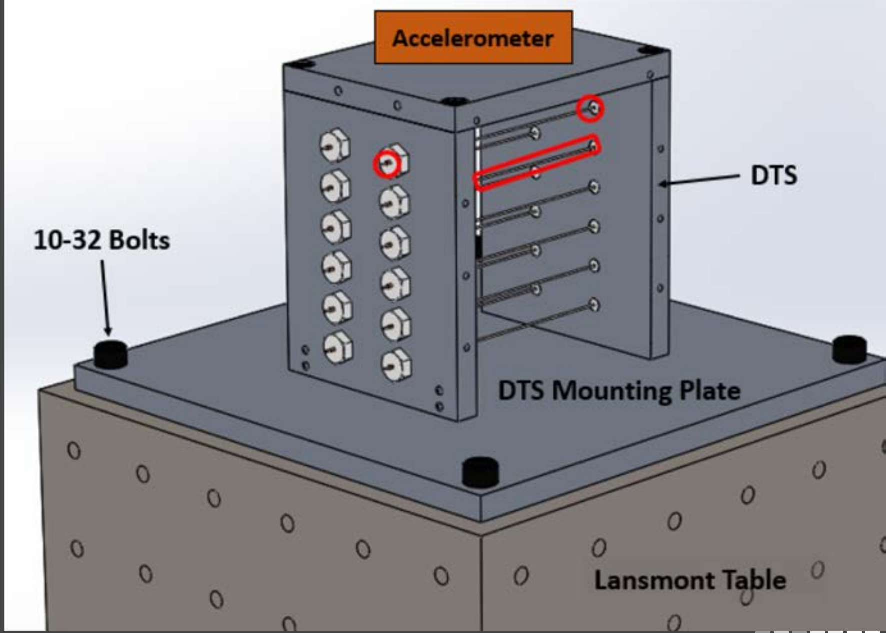
Verify that Wire Electrodes can withstand 10 m/s impact (Req 2.5.1)

Testing Set-up:

- Preliminary drops without DTS to determine drop height vs velocity relationship
- Wire electrodes installed as rigid bar (no slack) with no requirement for tension
- Analyzing for failure (wires free to move) at 3 locations after each test

Limitations:

- Only 1 DTS to test
- Material deformations are difficult to analyze



DTS Stand-alone

Verify wire electrode and CSA correctly respond to dust event

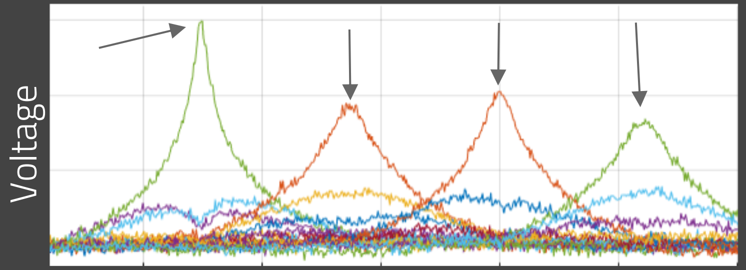
Purpose: Confirm the wire electrode connections and CSA conversion from charge to voltage, and signal amplification

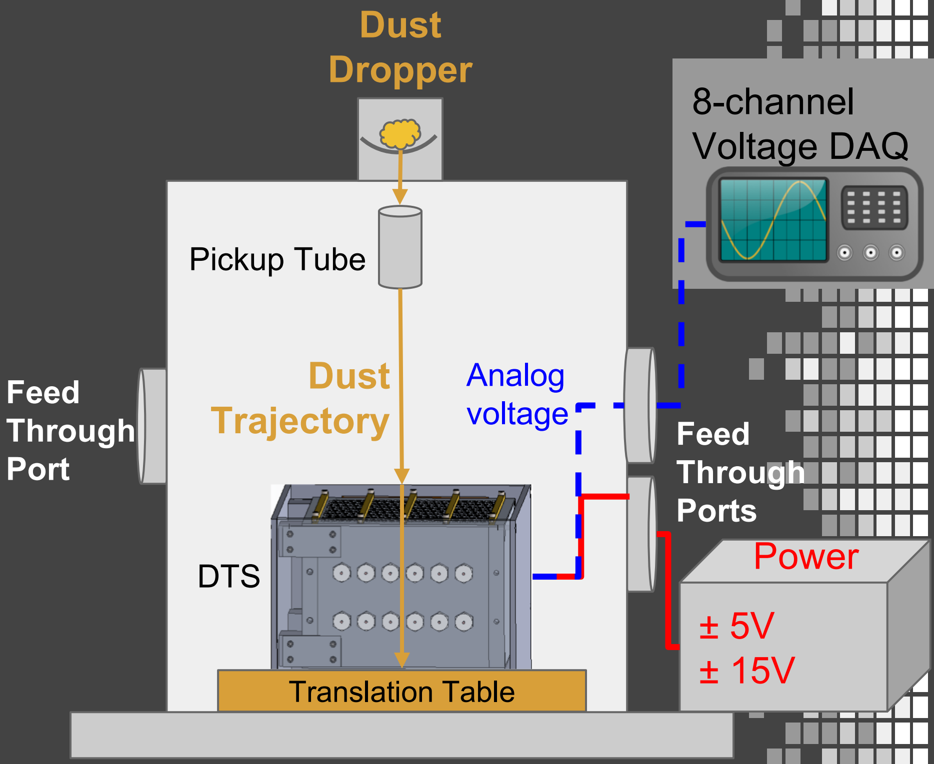
Facility: IMPACT no vacuum

Measure: Live analog voltage output from CSA board (8 wires at a time)

Success: Signal roughly matches expected shape and voltage magnitude (~2 V)

Sample Shape:



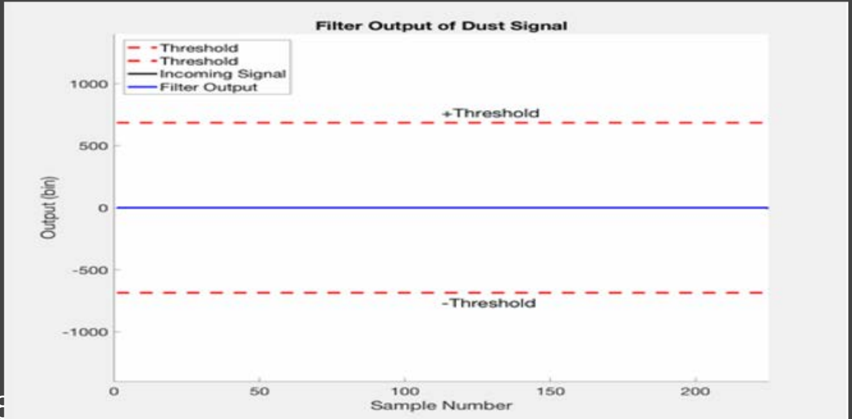


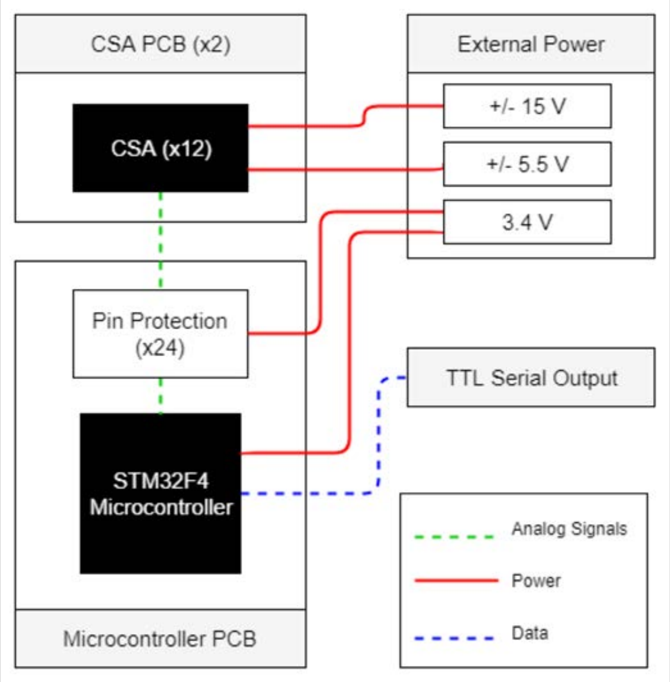
MCU/Trigger software

Verify trigger threshold and MCU data processing

Purpose: Test the ability of the trigger to correctly identify dust events and MCU's ability to process and send data over serial

Facility: IMPACT no vacuum
Output: CSA digital voltage over serial




CSA PCB (x2)
CSA (x12)
Pin Protection (x24)
STM32F4 Microcontroller
Microcontroller PCB
External Power
+/- 15 V
+/- 5.5 V
3.4 V
TTL Serial Output
Analog Signals
Power
Data

Electron Shield

Verify that electrons are repelled in TRL4 environment

Purpose: Verify magnetic shield blocks electrons up to 100 eV of energy which would cause noise on the wire electrodes

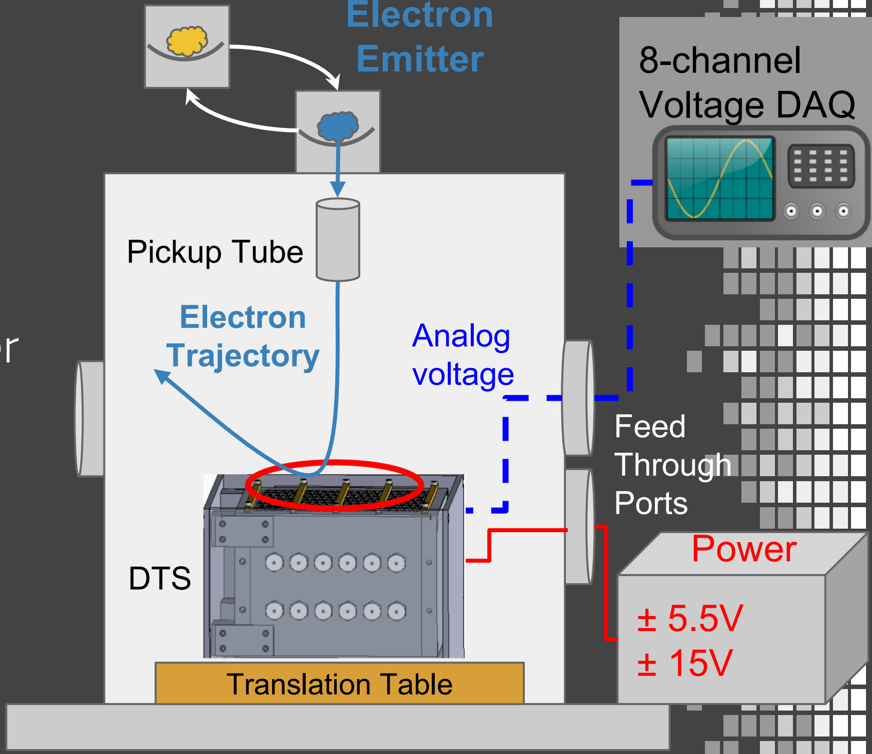
Facility: IMPACT vacuum (for free electrons)

Procedure:

- Replace dust dropper with electron emitter
- Apply set voltage to emit electrons up to 100 eV of energy
- Measure response from CSA over test duration (1 min)

Measure: Digital Voltage

Success: Null Voltage (random noise)



Full Instrument Test

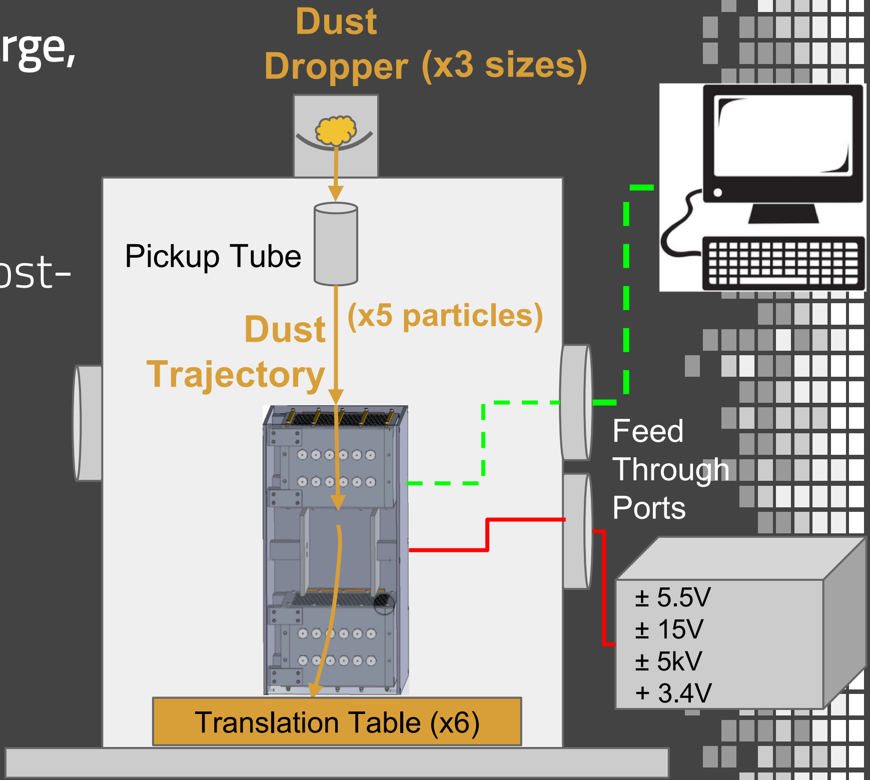
Verify that instrument detects dust particles that enter the instrument. Req 2, 5, 6

Purpose: Detect a dust event and extract the charge, mass, and velocity of the particle.

Facility: IMPACT vacuum

Measure: Output digital voltage in a data file to post-processing software, calculate charge, mass and velocity distribution (~90 dust events total)

Data Type	Expected Range
Charge (*Q*)	1 - 160 fC
Mass (*m*)	~100μg
Velocity (*v*)	1 - 2 m/s

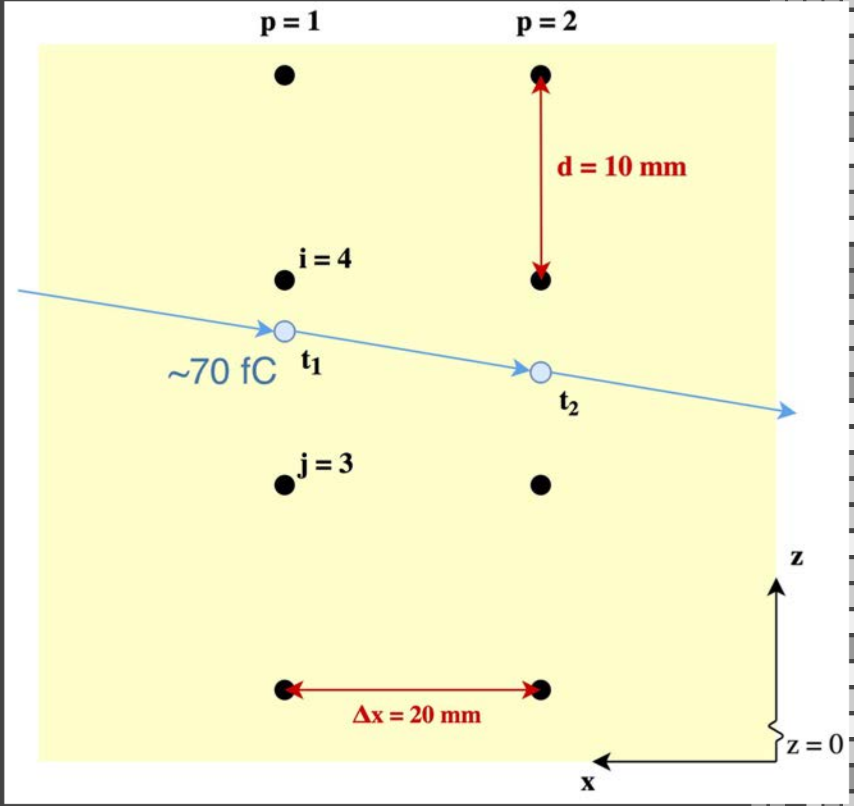


Methods for Q, v, & m extraction

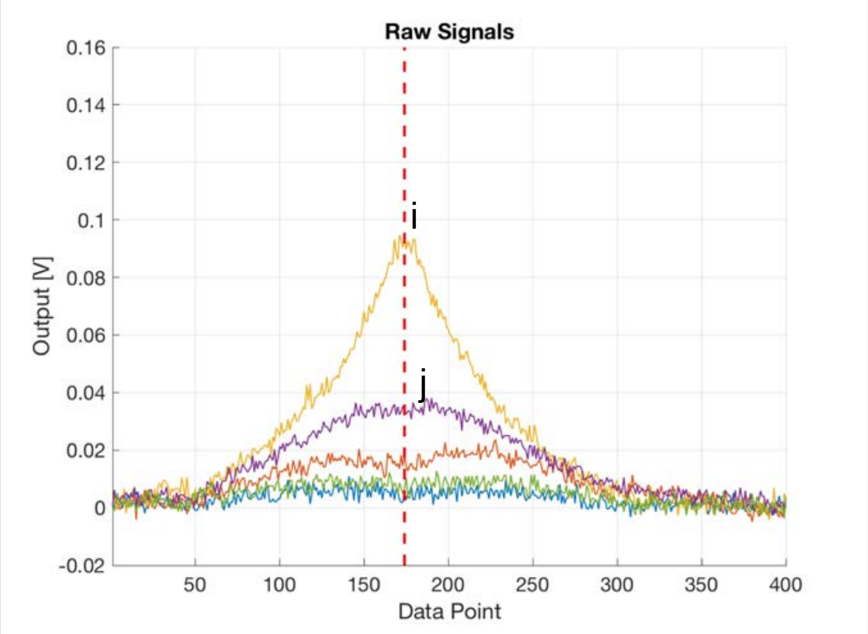
Definitions:

- 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)



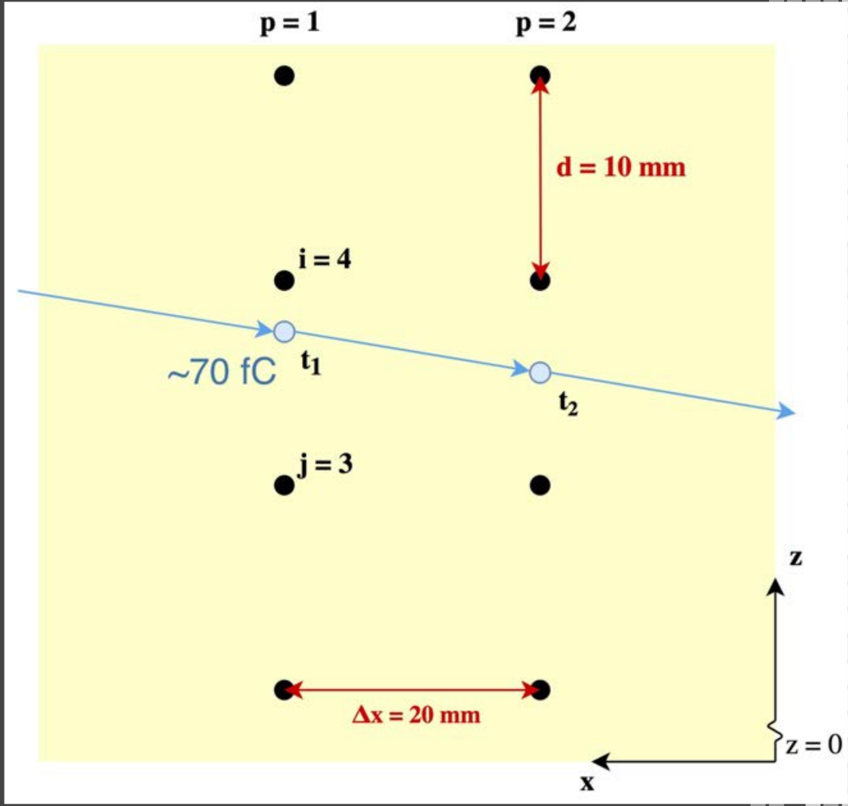
Methods for Q, v, & m extraction



Charge Sensitive Amplifier (CSA) creates voltage from induced charge:

Sensitivity: ρ =18 mV/fC

DTS Unit (sub-section)



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

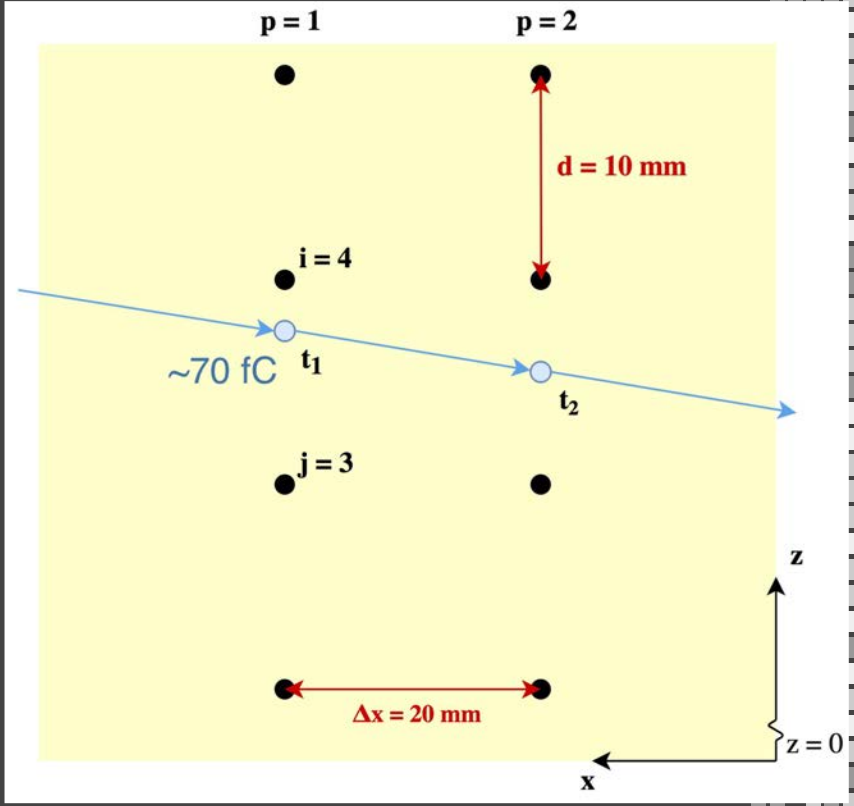
Steps:

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

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

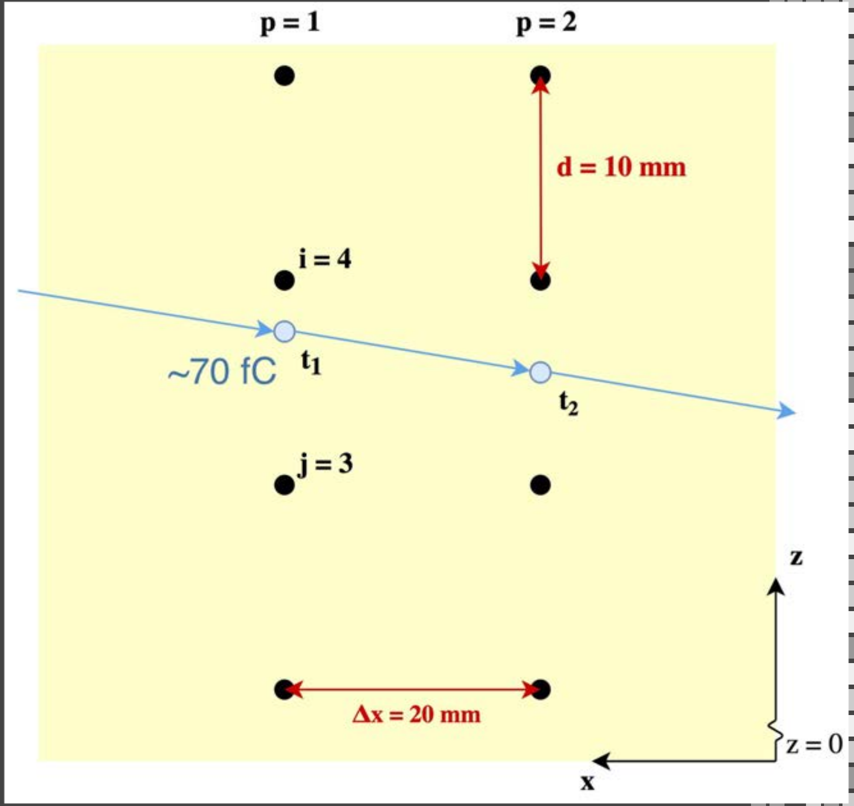
2. Absolute z-coordinate

$$\text{If } i > j \quad \rightarrow \quad z_p = h_i - d_i$$
$$\text{If } i < j \quad \rightarrow \quad z_p = h_i + d_i$$

2. Repeat steps 2 & 3 for every plane

$(p = 1 \longrightarrow 4)$

DTS Unit (sub-section)



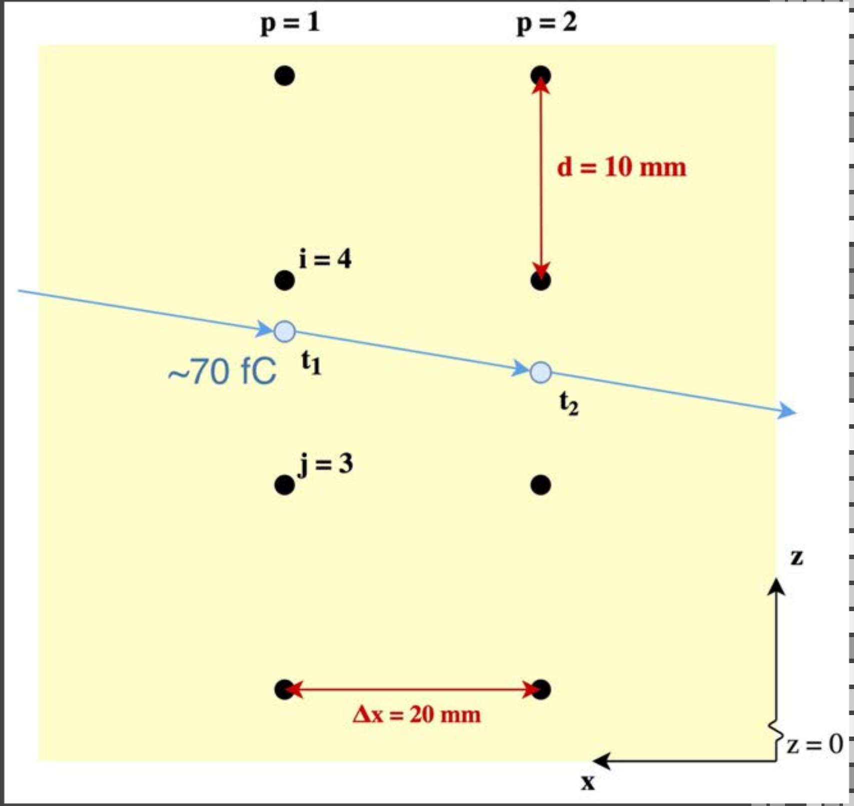
Methods for Q, v, & m extraction

Steps (Cont.):

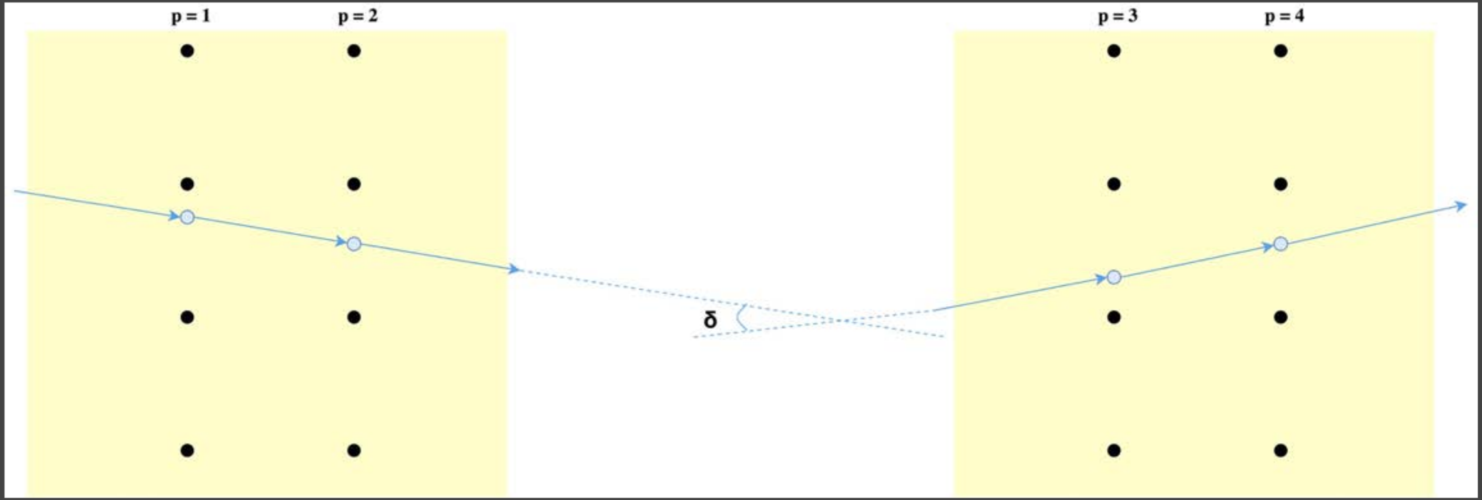
5. Velocity calculation

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

DTS Unit (sub-section)



Methods for Q, v, & m extraction

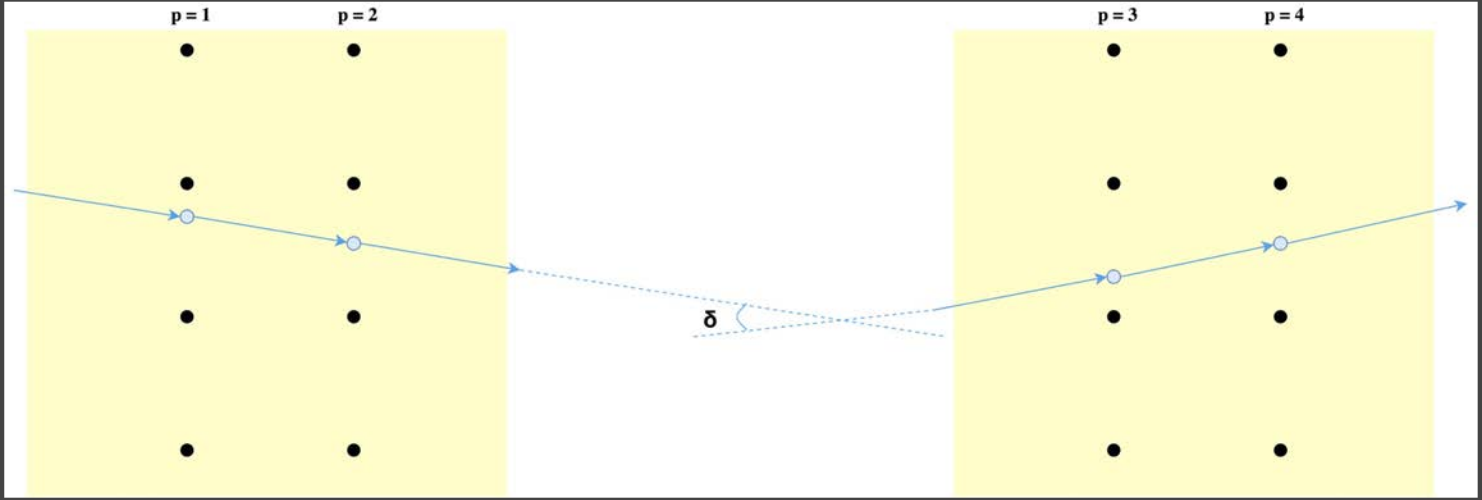


Steps (Cont.):

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.):

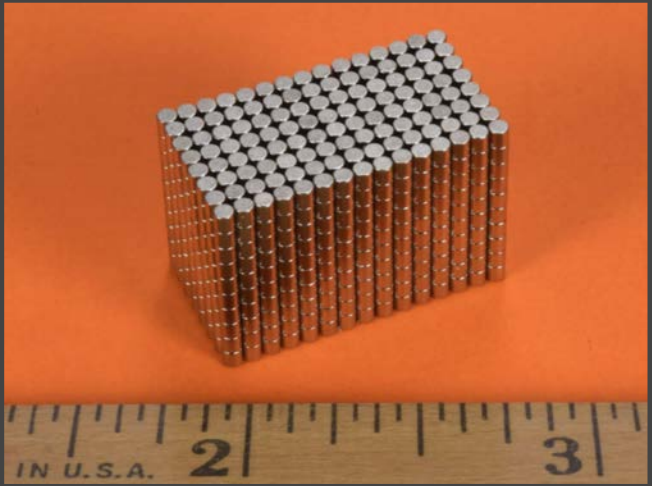
7. Calculate mass (where l = 0.07 m is the length of the deflection region)

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

Electron Deflection

Cylindrical magnets:

$D = 1.59 \pm 0.10$ mm
$t = 1.59 \pm 0.10$ mm
Magnetic Remanence:
$B_r = 1.48$ T



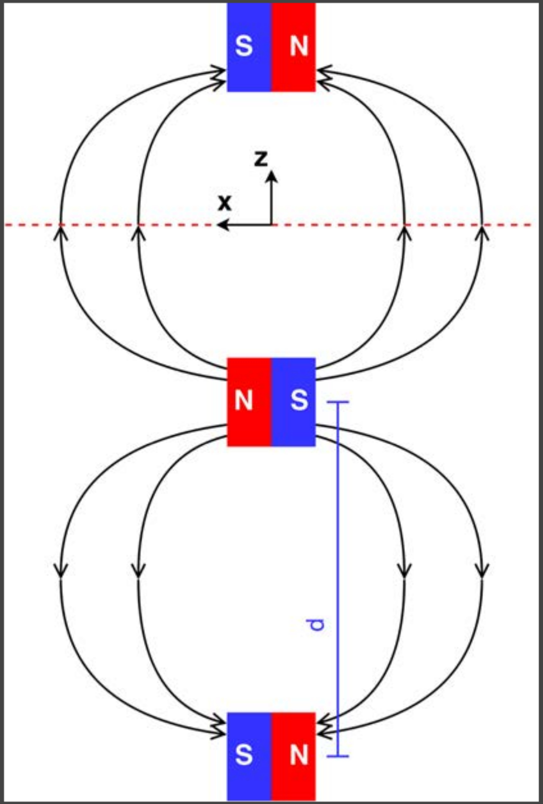
Need to prove gyroradius of 100 eV electron to be sufficiently as to not penetrate the instrument more than 1 cm (first wire plane)

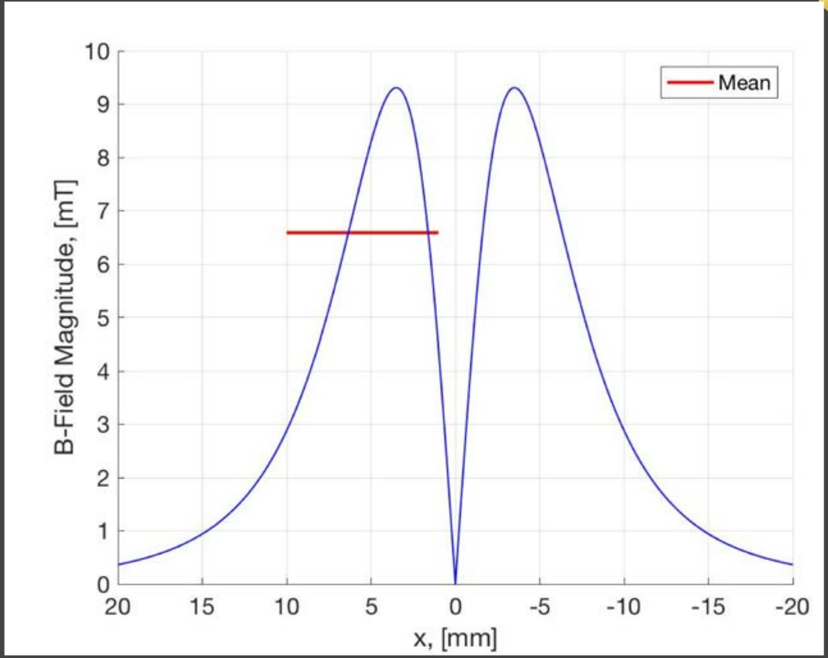
Gyroradius:

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

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)

Characterization of Sun-sensing

Verify the system can find the sun to within 1° over the full sky.

Requirements 3.21 and 3.22

Purpose: Characterize the accuracy of the photodiodes, covers, and algorithm across the sky.

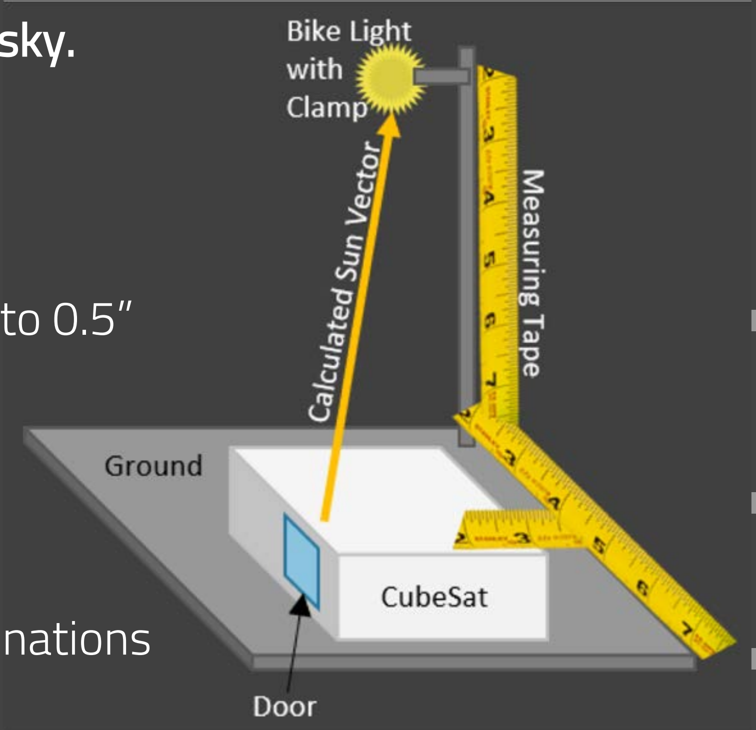
Facility: Bobby's Lab with overhead lights off

Measurements:

- Measured light source position
  - 5ft distance to source, know position to 0.5" for 0.5°
- CubeSat calculated sun vector
  - Based on photodiode measurements

Full sky characterization:

- 32 locations that use all photodiode combinations

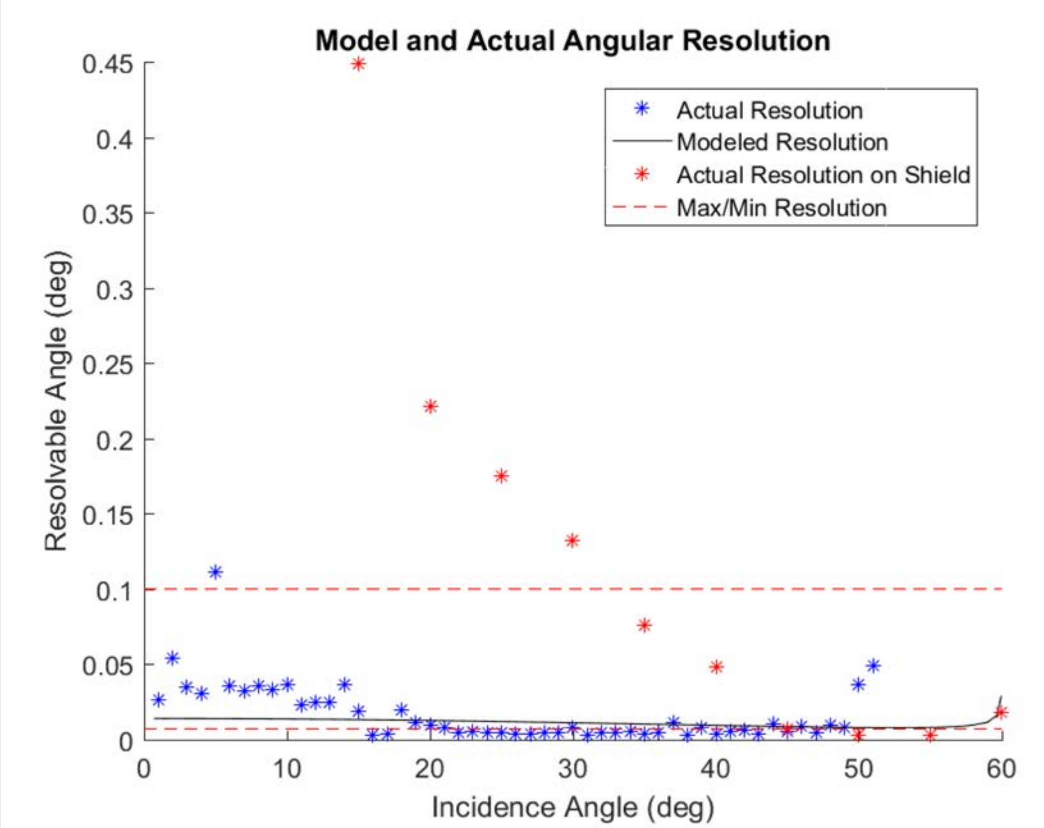


Sun Sensing Problems/Issues

Did not realize we could have too much resolution

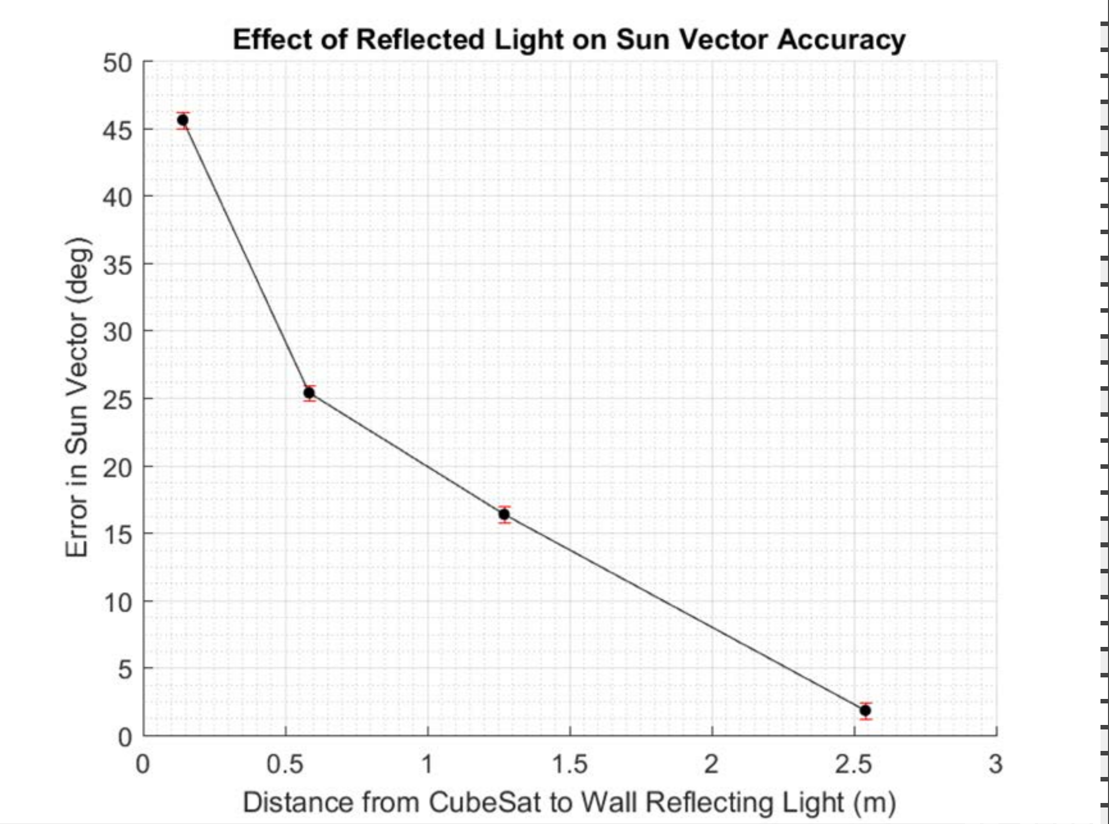
There is a minimum resolution

Did not add margin to minimum



Reflected Light Caused Additional Errors

- Designed ambient light margin reduced due to unexpected roll-off
  - Sun sensing was not tolerant to reflected light
- Testing locations were chosen away from walls to compensate
  - No requirement for testing environment



Integrated Tilting and Sun-sensing

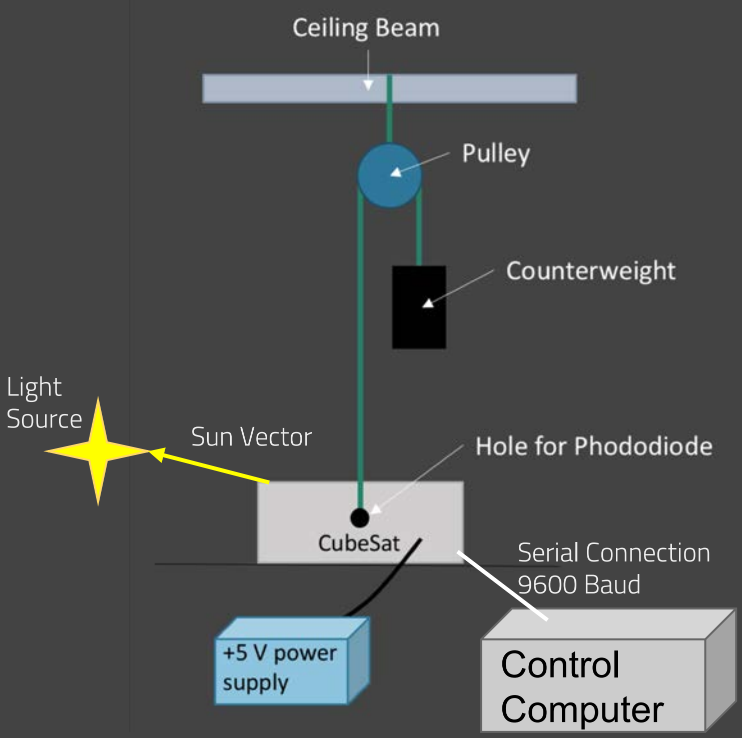
Verify integration of tilting mechanism, door, and sun sensing for 1° accuracy and closed-loop tilting - Requirements 3 and 4

Purpose: Measure the tilt angle of the Cubesat as it responds to light locations

Facility: Senior Project Depot

Measurements:

Tilting angle of the cubesat using accelerometer - compare to calculated ideal tilt based on actual light source position



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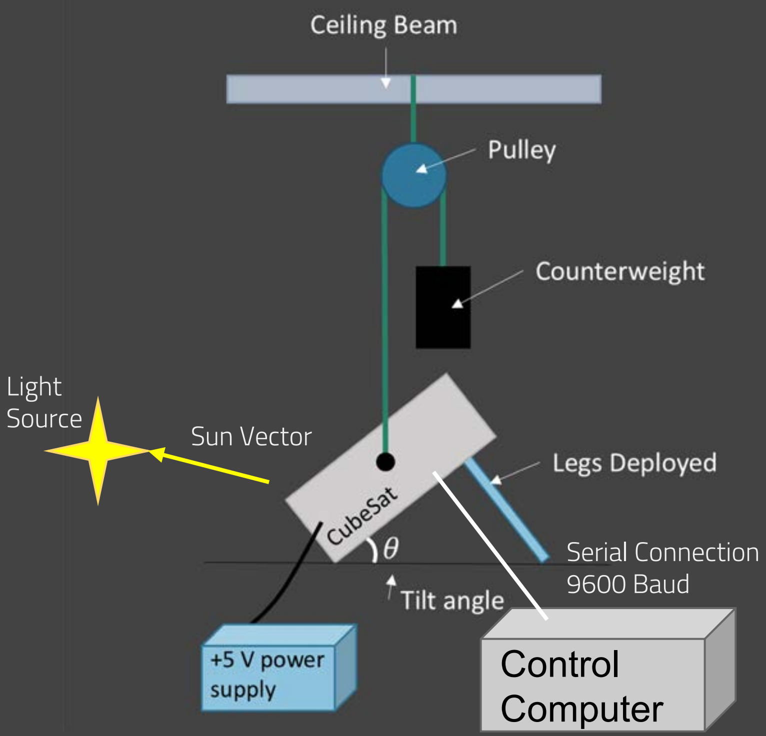


Photodiode Cover Calibration

Verify the photodiodes can measure the sun angle to within 0.5° over the 60° field of view. Requirements 3.21 and 3.22

Purpose: Provide a calibration for the photodiode output to sun angle

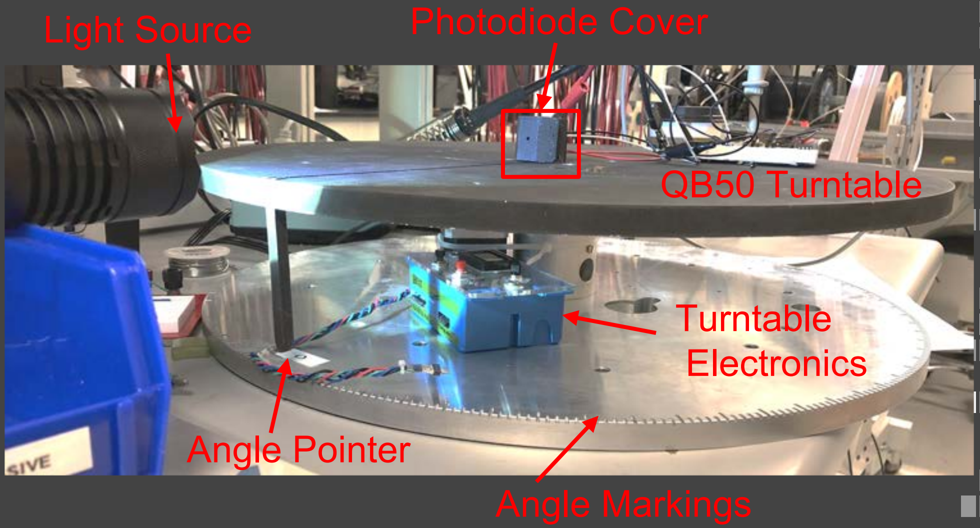
Facility: Bobby's Lab

- Cubesat
- QB50 Turntable
- Light Source (bike light)
- 5V Power Supply

Measurements: Output voltage to oscilloscope

Procedure:

- Set up turntable and photodiode
- Turn 1° increments, measure voltage



Photodiode Vector Calibration

Verify the pointing of each individual photodiode. Requirements 3.21 and 3.22

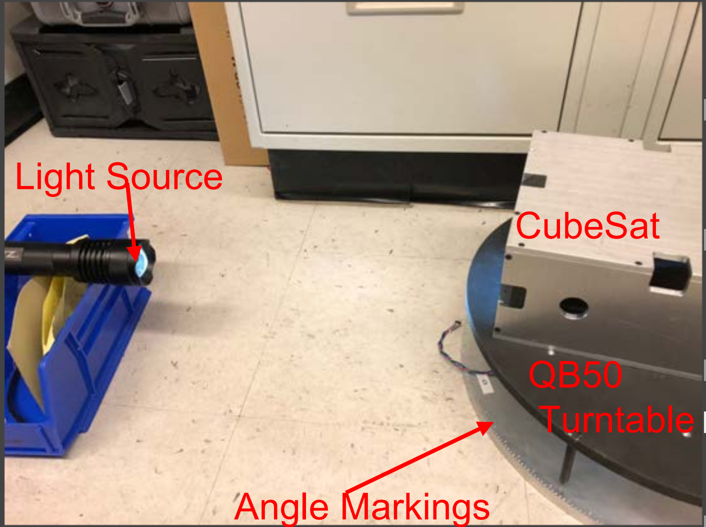
Purpose: Provide a calibration for the pointing of each photodiode on the CubeSat

Facility: Bobby's Lab

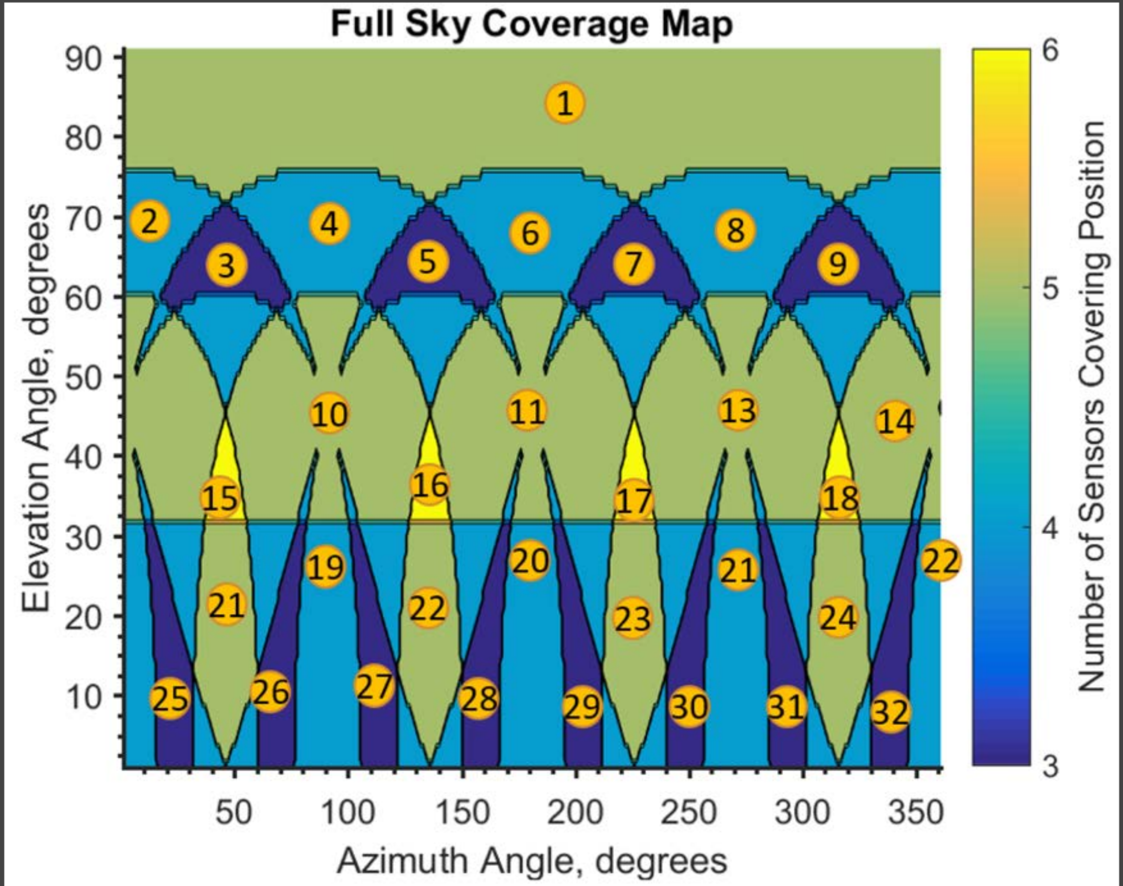
- Cubesat
- QB50 Turntable
  - 1 increments, 0.25" to within 0.005"
- Light Source (bike light)
- 5V Power Supply

Measurements: Output voltage

to microcontroller, resulting sun angles



Sun Sensing Characterization Locations



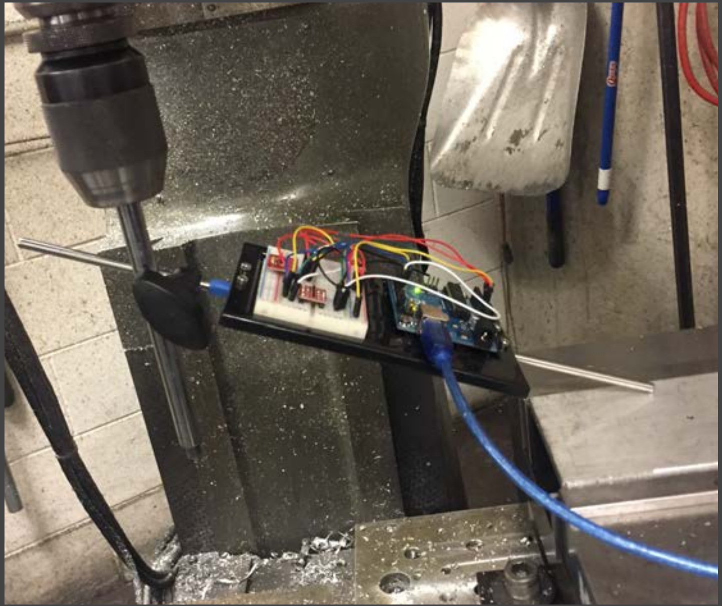
Accelerometer Testing

Verify that accelerometer can resolve less than 0.5 degree tilt angle

Characterization of noise levels of digital output

Machine Shop
- ADXL345 Triple Axis Accelerometer
- CNC
- Accelerometer mount

Procedure (this can also be a diagram)
- Calibrate accelerometer
- Take data at level (0 deg tilt) (10 s)
- Move CNC known amount
- Take data at tilt (10s)
- Compare measure to computed
- Repeat

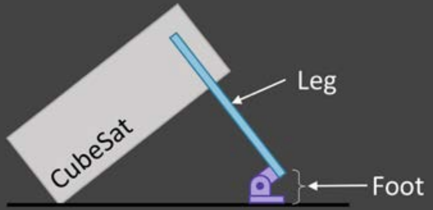


Vacuum Chamber Preparations

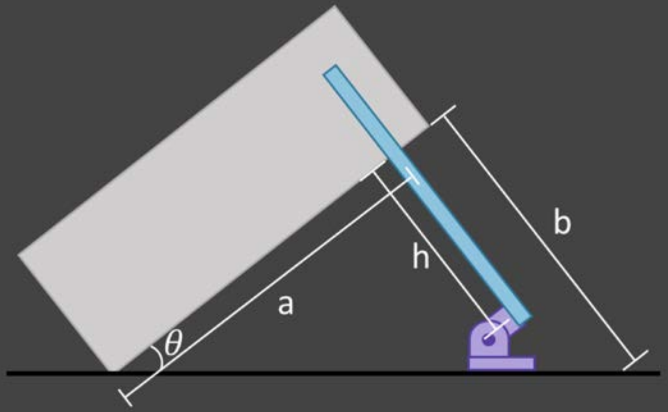
- Cleaning
  - Alcohol/flux remover cleaning for PCBs
  - Acetone and ethanol cleaning in ultrasonic bath for machined components
  - Cleaned instrument stored in ESD bag for transport
- Proper Material Selection
  - Low outgassing materials: aluminum, PEEK, Delrin
  - Vented Bolts

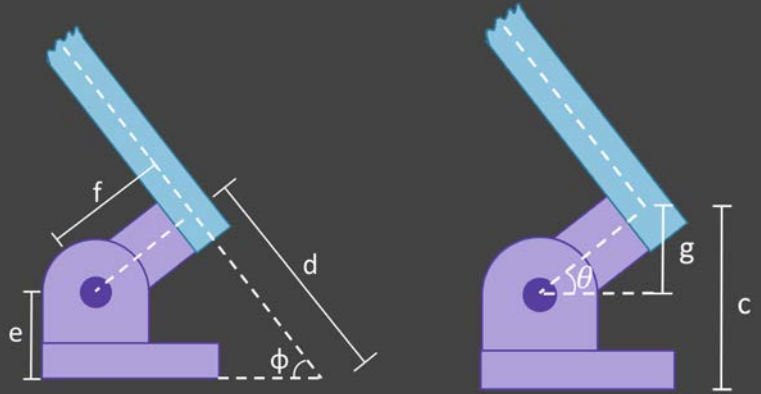
Tilting Backup Slides

Scissor Lift Tilting Algorithm



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





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

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

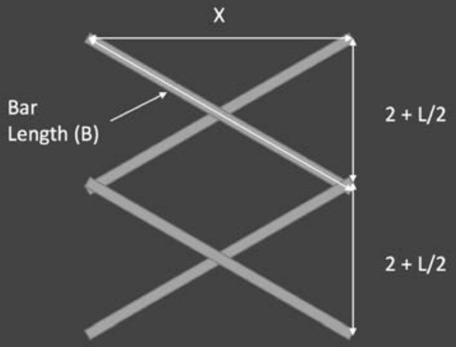
$$c = e + g$$

$$h = b - d$$

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 = $\Delta X = X - X'$

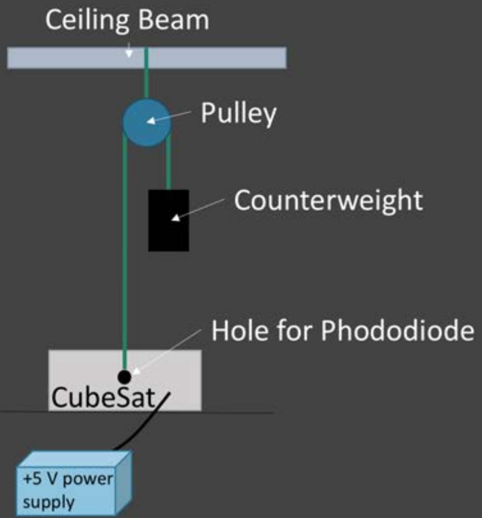
Open Loop Tilt Testing

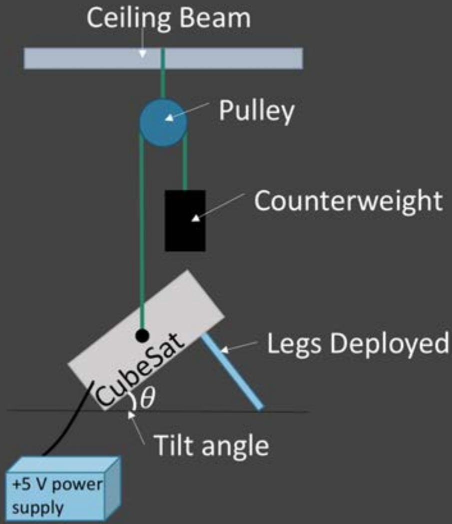
Verify the tilting mechanism can tilt the instrument up to 45° in 1° increments (+/- 0.5° accuracy) - Requirements 4.12,4.121

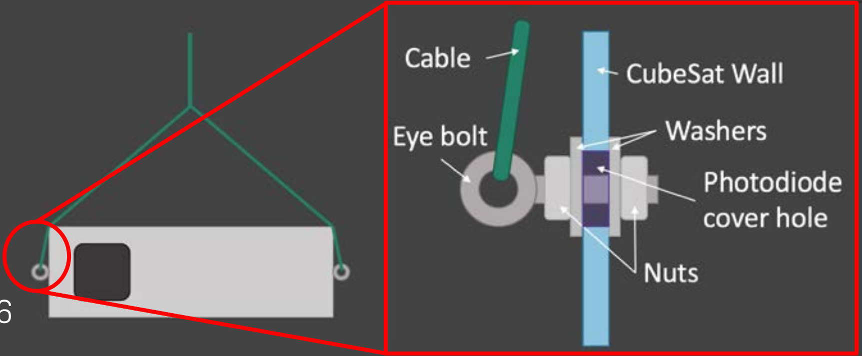
Purpose: Measure the tilt angle of the Cubesat relative to level ground in 1° increments

Facility: Senior Project Depot

Measurements: Tilting angle of the CubeSat using accelerometer

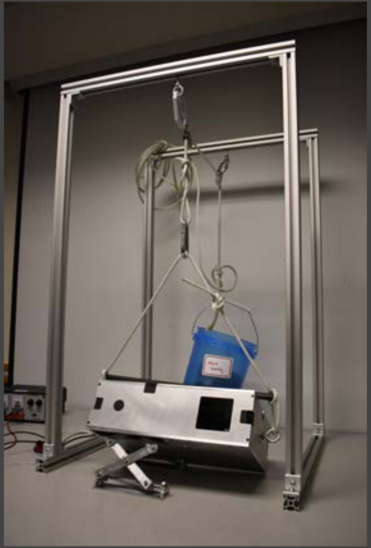




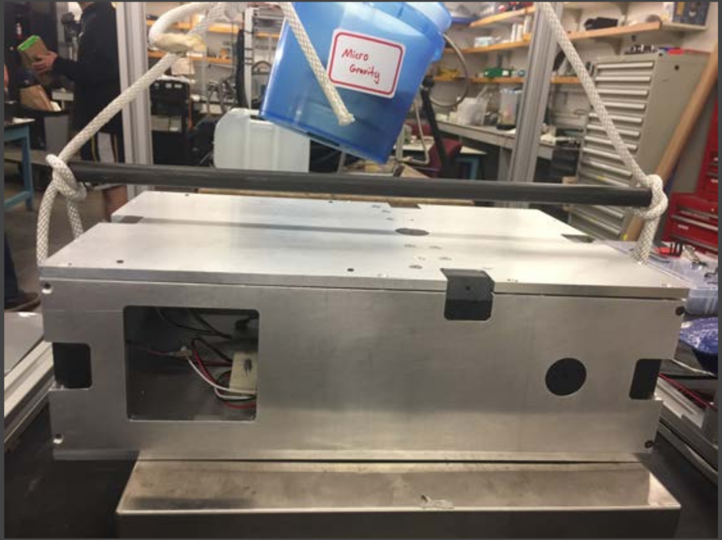


Tilt Testing Changes

Added a second pulley to reduce risk of bucket hitting cubesat



Added a support to prevent rope from resting on body



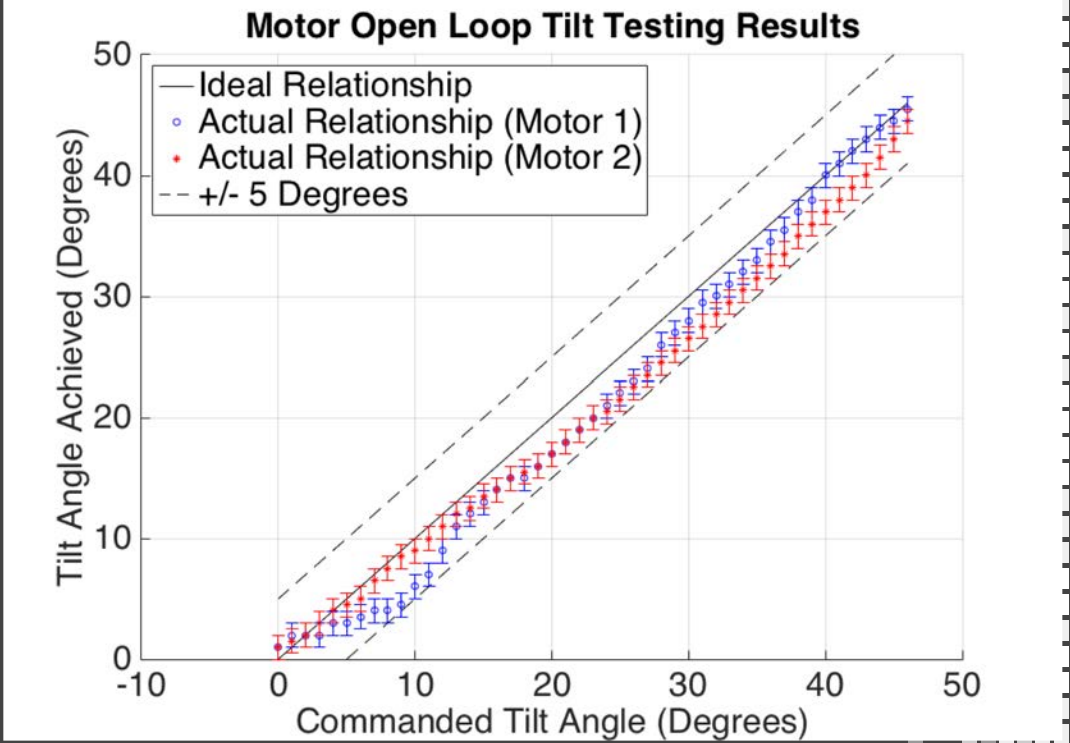
Other Evidence of Friction

Cubesat became suspended while tilting back down over large increments

Open-Loop Tilting Results

Sending commands to the Teensy to step the motors by a predetermined amount based on our model

Meets 2nd level of success (Open loop tilting accuracy of +/- 5°)

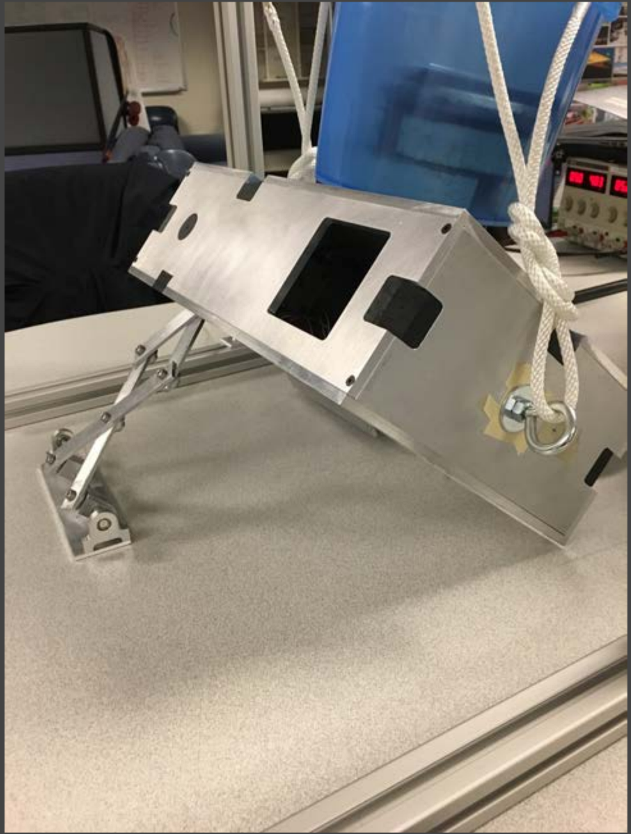


“Locked” Tilting Results

After tilting, another requirement was to ensure that the motor could hold the weight of the cubesat

- Turned off power and left cubesat tilted for 5 minutes and overnight
- Tilt angle did not change in either case

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



Door Testing

Purpose: Ensure the Door Opens Correctly

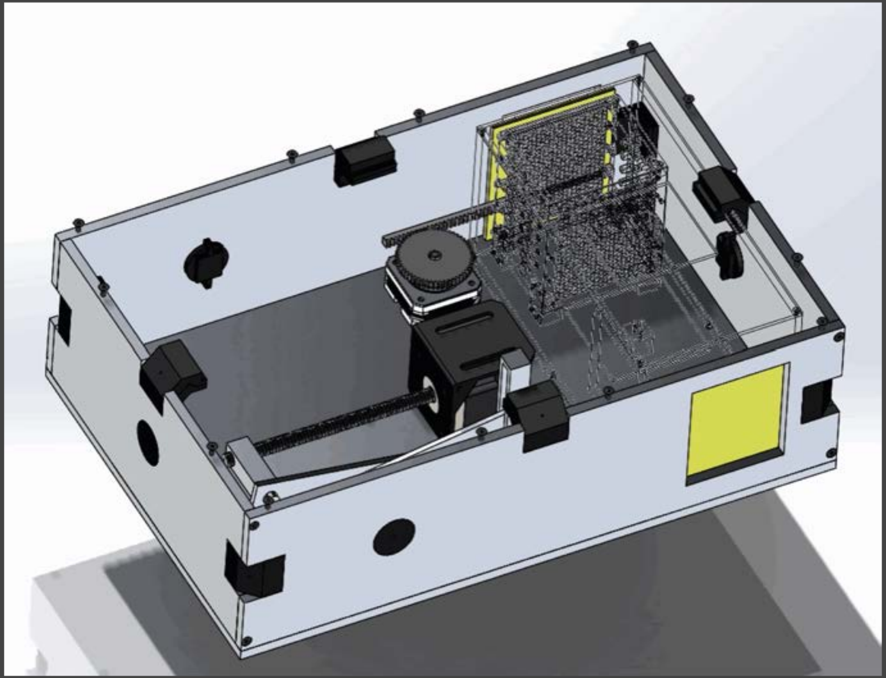
Facility: Senior Project Depot

Measurements:

- Does the door protect this instrument

Procedure:

- Attach door to power supply and Teensy
- Activate door mechanism at level and tilting platform



Door Testing Results

Manufacturing issues led to Doors not being able to fit inside of Cubesat

Unable to test if the door operated as intended

Would require more time to implement some fixes

Requirement 3.11, 3.12
Incomplete

Photodiodes Boards

Verify functionality of PCB and overall design

Voltage relative to intensity of light

- Ambient light ___mV

Electronics lab

- Power supply (5V)
- Oscilloscope/multimeter

Procedure

- Connect PCB to power supply and measuring device
- Turn on and check readout in ambient light
- In a dark room, position light source 5ft away and check readout at different angles

Teensy Shield Test (backup)

Verify functionality of PCB and filter design

Fit check, verify all components are powered correctly and outputting information

Electronics lab

- Power supply (5V)
- Oscilloscope
- Multimeter

Procedure

- Fit check all COTS boards (do not solder on yet)
- Connect to power supply and check proper power distribution
- Connect photodiode and check output after filter
- Solder on COTS boards one at a time and check functionality of each

Impact Testing Models

Rigid Bar Statics Model
- Wire’s fail at 4 N impact force
- Unable to correlate impact velocity to impact force without impact time

Solidworks Model
- Proper Material Selection
- 10 m/s impact results show stresses not exceeding failure stress

Impact Testing Model

Assumptions

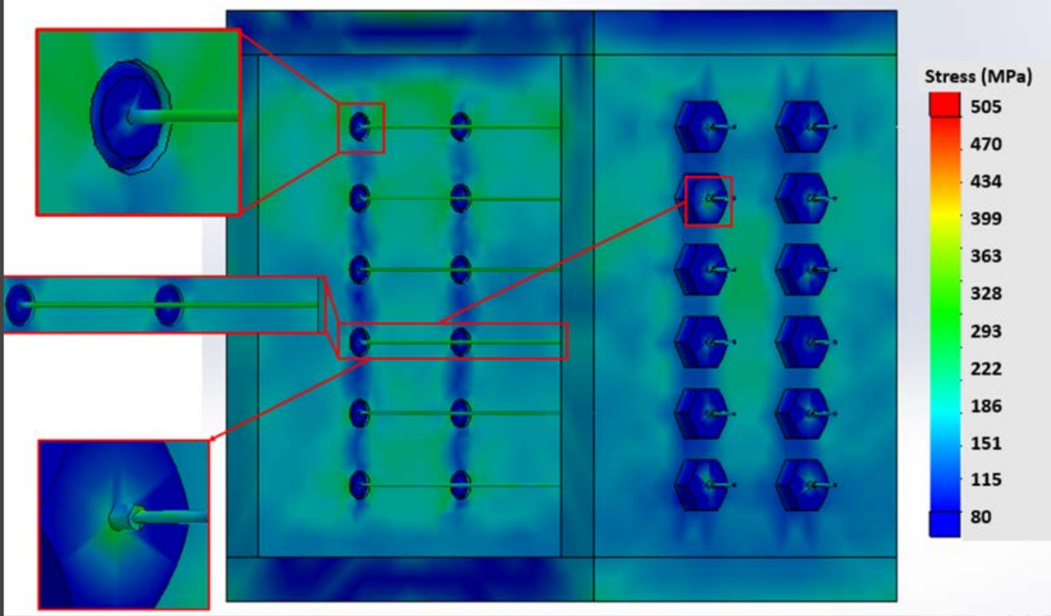
- Entire DTS is bonded
- Landing on rigid surface
- Perfectly inelastic collision

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



Lansmont Drop Test Procedure

Step 1: Input desired drop height.

2: Raise testbed to desired drop height.

3: Once in position, run LabView VI to record voltage and drop the testbed.

4: After completing drop, stop the VI (VI will save the drop data).

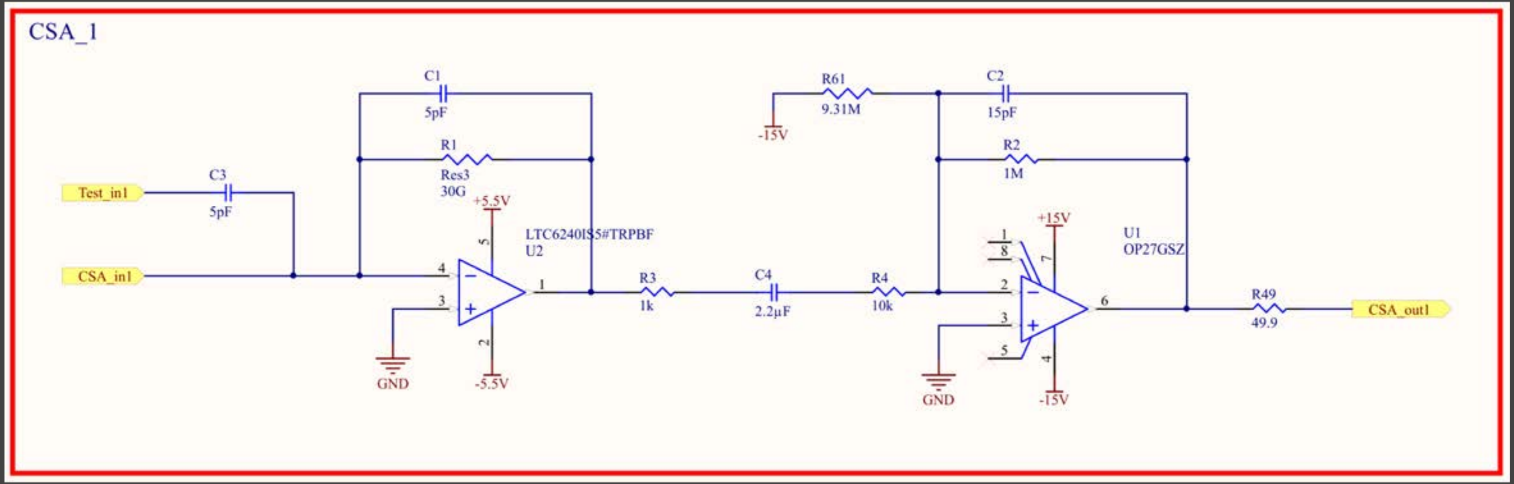
5. Repeat procedure for new drop height

Post-process voltage data to calculate acceleration. Integrate acceleration to determine impact velocity.

Drop Height (cm)	10	20	30	40	50	60	70	80	90	100	110	120	127
Impact Velocity (m/s)	0.8	1.6	2.1	2.5	2.9	3.2	3.5	3.7	4.0	4.3	4.5	4.7	4.9

Drop Test Footage

CSA Verification: Model



Ideal op-amp model assumed

$$V_{out} = \frac{Q_{dust} G_2}{C_{fb}}, \quad Q_{dust} \approx Q_{test\ cap}$$

$$Q_{test\ cap} = C_{test} V_{test}$$

Embedded System Status cont.

Hardware/software integration incomplete

Infeasible given time and resources—two team members responsible for:

- Custom instrument embedded system (low-noise analog electronics and digital system)
- Real-time embedded software designed and implemented using LASP Ada-based flight software framework, Adamant

Functional requirements not met:

5. The electronics subsystem shall collect signals and issue commands to and from the instrument [...]
6. The software shall be capable of [...] detecting dust events [...]

Software Framework

What is Completed

Implemented dust detection algorithm
Error events for ADC missampling or incorrect timing
User serial input commands to start and stop data collection, reset data buffers, and flip polarity of the instrument
Serial output of dust event data once dust particle is found

What could not be finished

Hardware/Software integration which includes setting up the ADCs, DMA, MCU, and hardware interrupts

Why it wasn't finished

Lack of team knowledge and time for software/hardware integration
Difficulty in using open-source Ada STM32F4 drivers within framework

Integrated Tilting and Sun-sensing

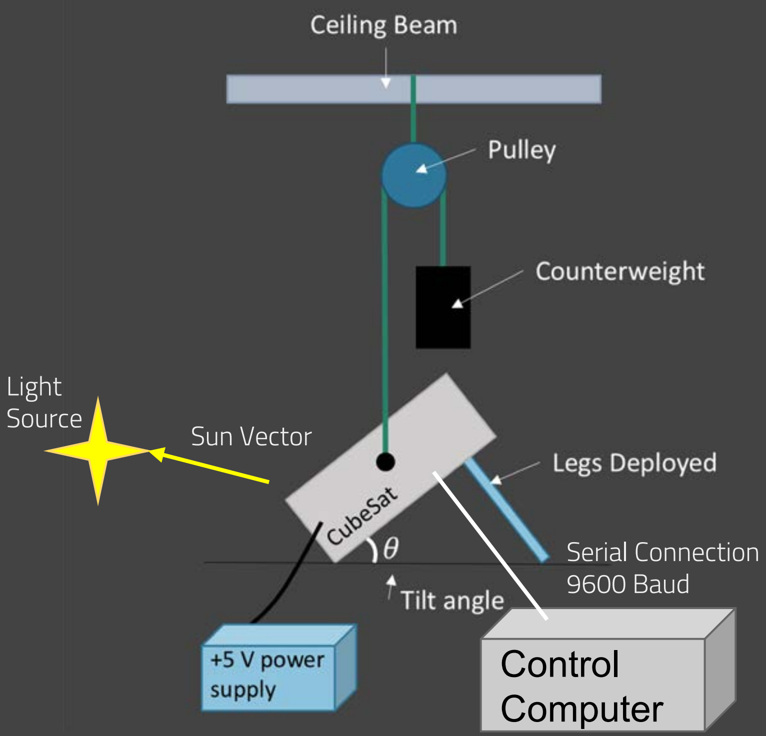
Verify integration of tilting mechanism, door, and sun sensing for 1° accuracy and closed-loop tilting - Requirements 3 and 4

Purpose: Measure the tilt angle of the Cubesat as it responds to light locations

Facility: Senior Project Depot

Measurements:

Tilting angle of the cubesat using accelerometer - compare to calculated ideal tilt based on actual light source position



Photodiode Cover Calibration

Verify the photodiodes can measure the sun angle to within 0.5° over the 60° field of view. Requirements 3.21 and 3.22

Purpose: Provide a calibration for the photodiode output to sun angle

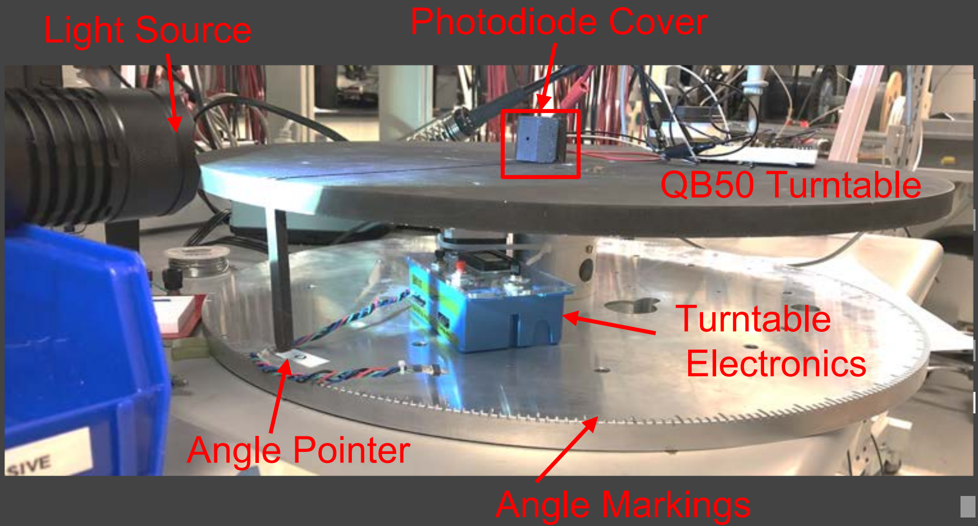
Facility: Bobby's Lab

- Cubesat
- QB50 Turntable
- Light Source (bike light)
- 5V Power Supply

Measurements: Output voltage to oscilloscope

Procedure:

- Set up turntable and photodiode
- Turn 1° increments, measure voltage



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Verify the pointing of each individual photodiode. Requirements 3.21 and 3.22

Purpose: Provide a calibration for the pointing of each photodiode on the CubeSat

Facility: Bobby's Lab

- Cubesat
- QB50 Turntable
  - 1 increments, 0.25" to within 0.005"
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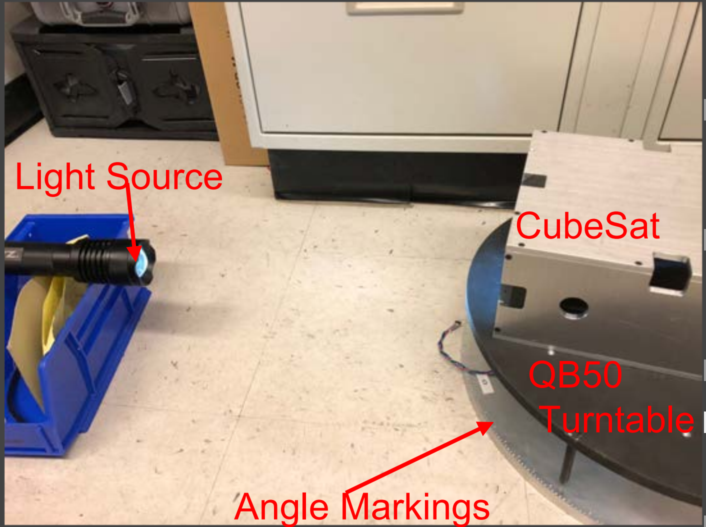
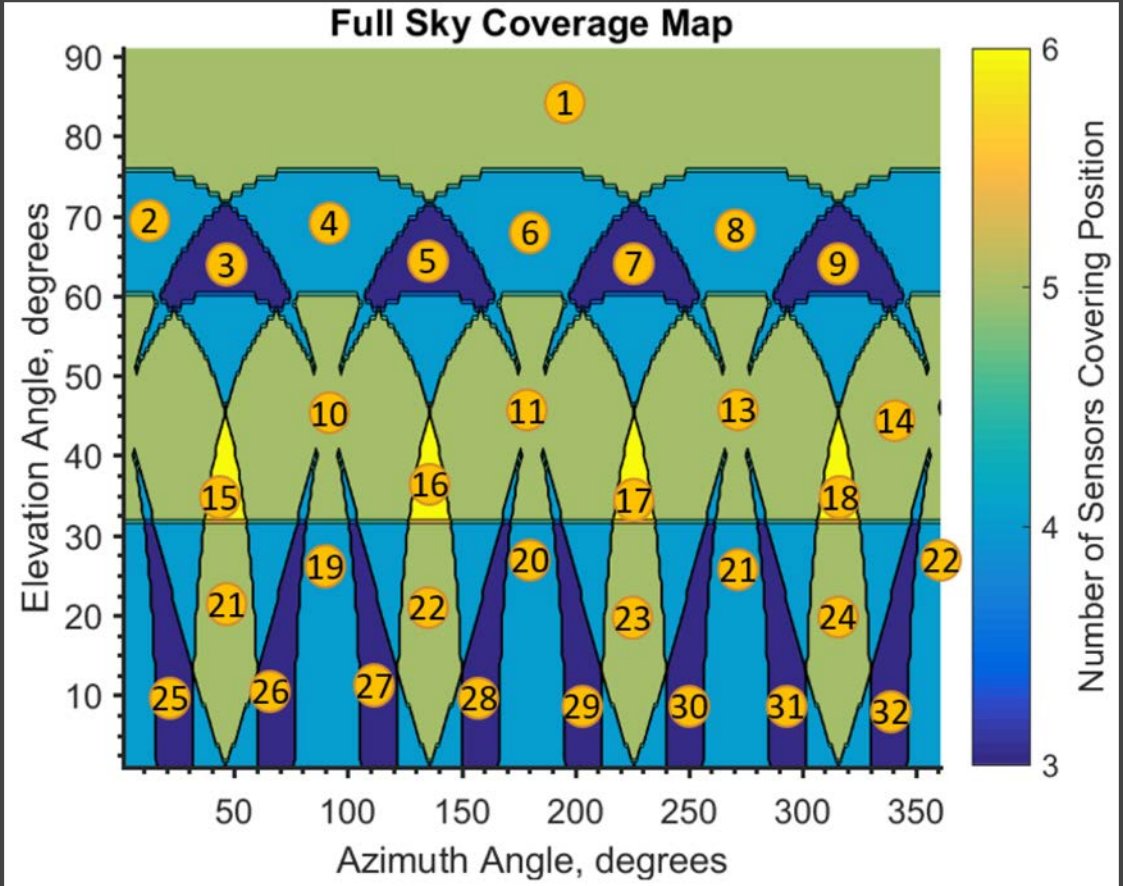
- 5V Power Supply

Measurements: Output voltage

to microcontroller, resulting sun angles



Sun Sensing Characterization Locations



Photodiodes Boards

Verify functionality of PCB and overall design

- Voltage relative to intensity of light
  - Ambient light 550mV
- Electronics lab
  - Power supply (5V)
  - Oscilloscope/multimeter

- Procedure
  - Connect PCB to power supply and measuring device
  - Turn on and check readout in ambient light
  - In a dark room, position light source 5ft away and check readout at different angles

Teensy Shield Test (backup)

Verify functionality of PCB and filter design

Fit check, verify all components are powered correctly and outputting information

Electronics lab

- Power supply (5V)
- Oscilloscope
- Multimeter

Procedure

- Fit check all COTS boards (do not solder on yet)
- Connect to power supply and check proper power distribution
- Connect photodiode and check output after filter
- Solder on COTS boards one at a time and check functionality of each

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.

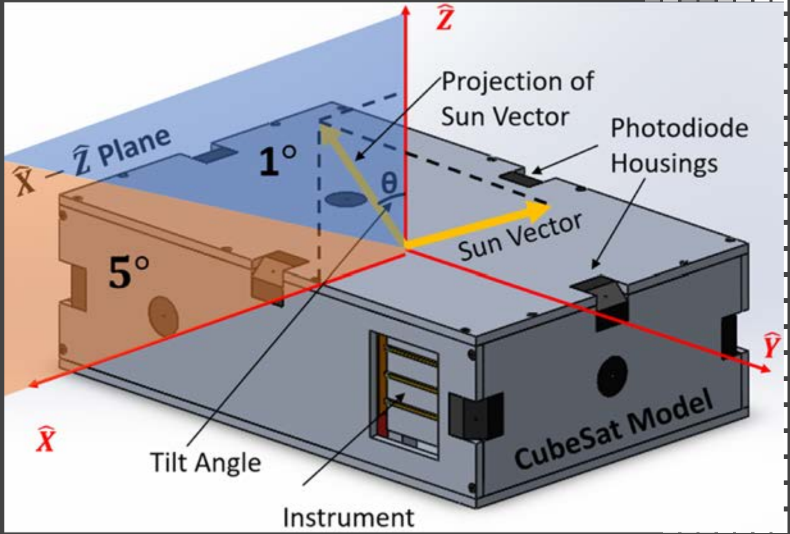
Why?

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

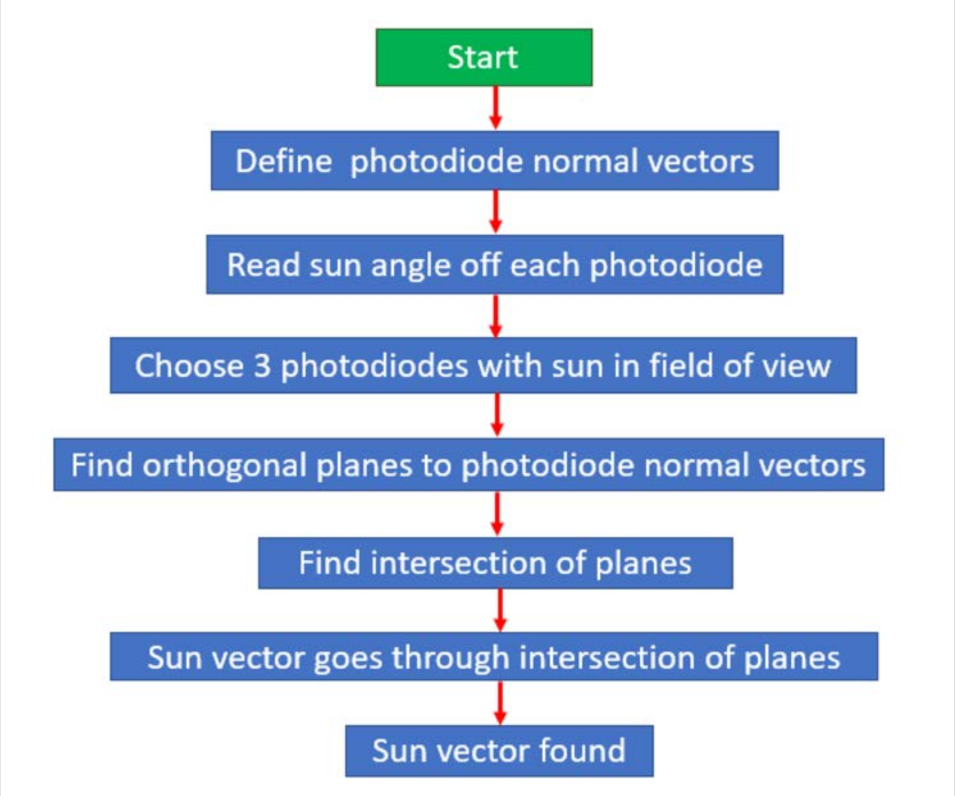
Designs Driven:

Sun determination algorithm

Photodiode placement



Sun Finding Algorithm



Start

Define photodiode normal vectors

Read sun angle off each photodiode

Choose 3 photodiodes with sun in field of view

Find orthogonal planes to photodiode normal vectors

Find intersection of planes

Sun vector goes through intersection of planes

Sun vector found

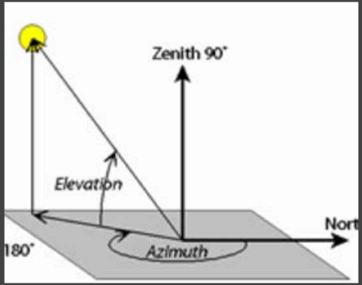
Full Sky Coverage

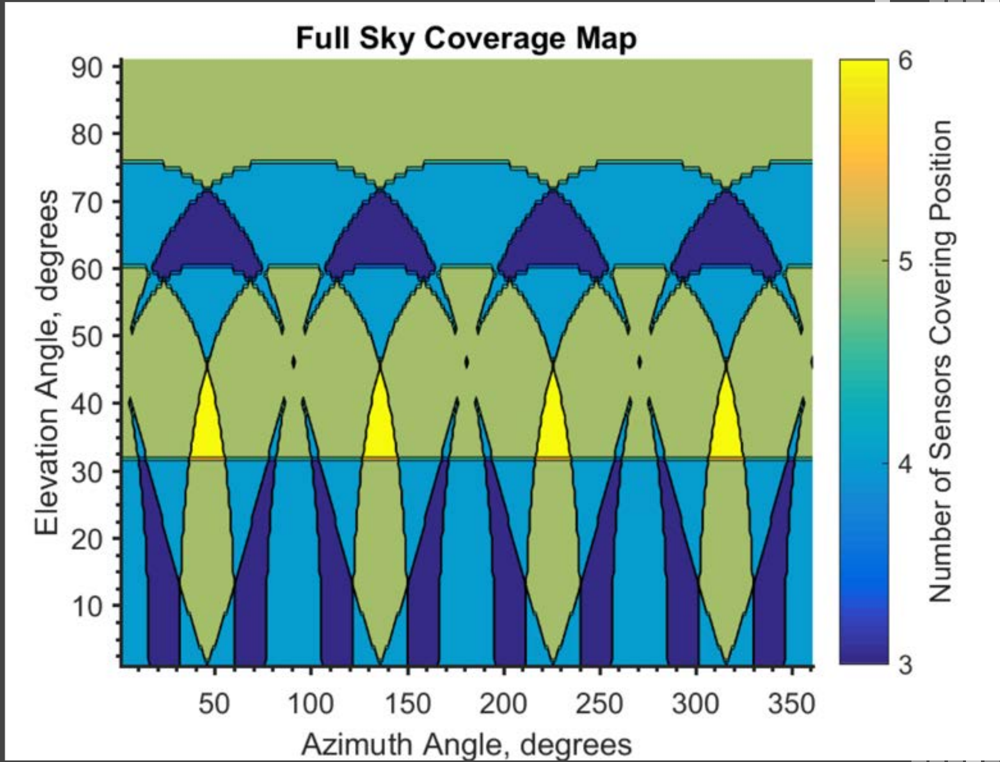
- 3 measurements required to find sun
  - Full sky must be covered by 3 photodiodes at minimum
  - Map shows number of sensors that see each position in the sky

3 Photodiode Minimum

↓

Requirement 3.2.4 satisfied



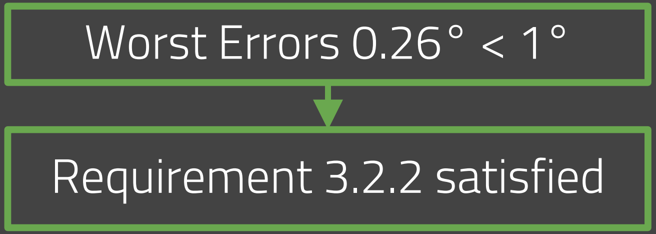


Nominal Design Case

Varied thermal and sampling noise uniformly

Move sun vector over full sky

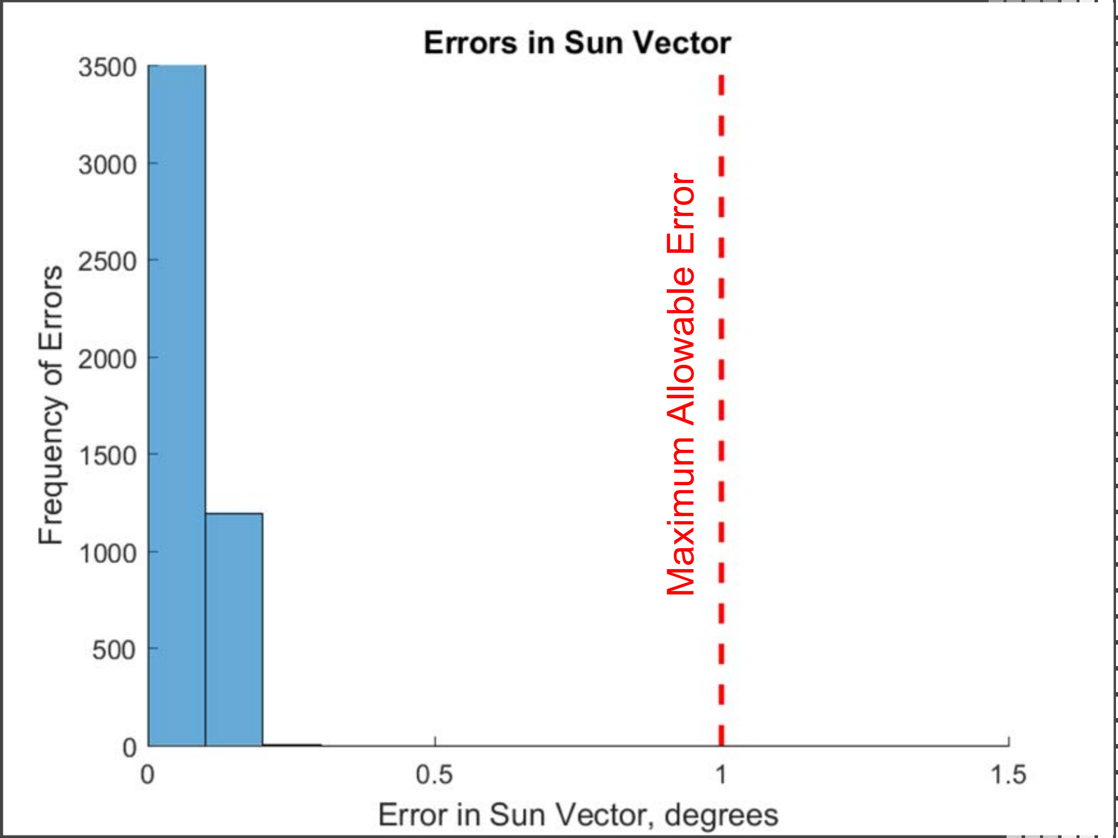
Maximum error in sun vector is 0.26°



Worst Errors 0.26° < 1°

Requirement 3.2.2 satisfied

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

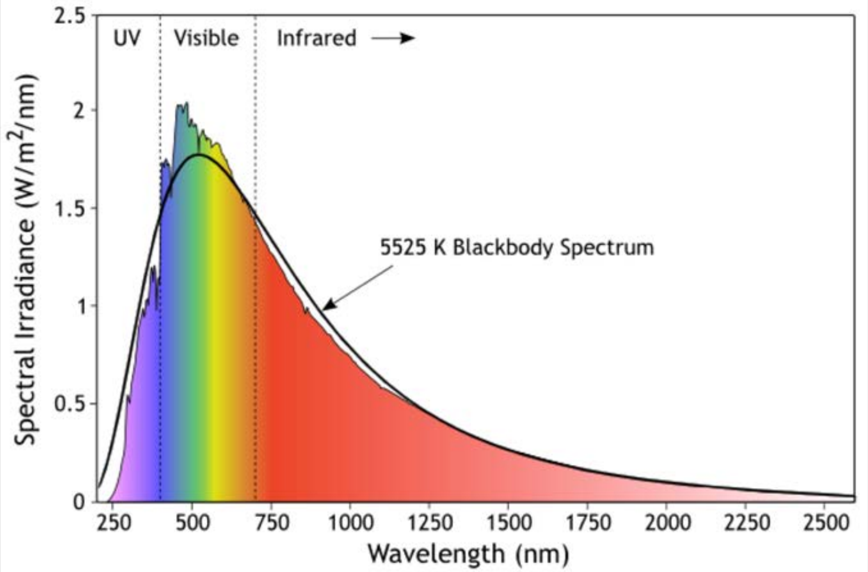


ARS Component Level Tests

- 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



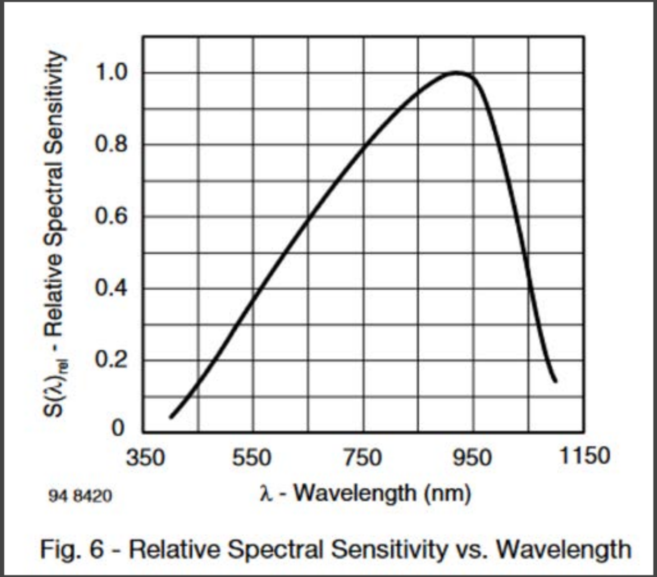
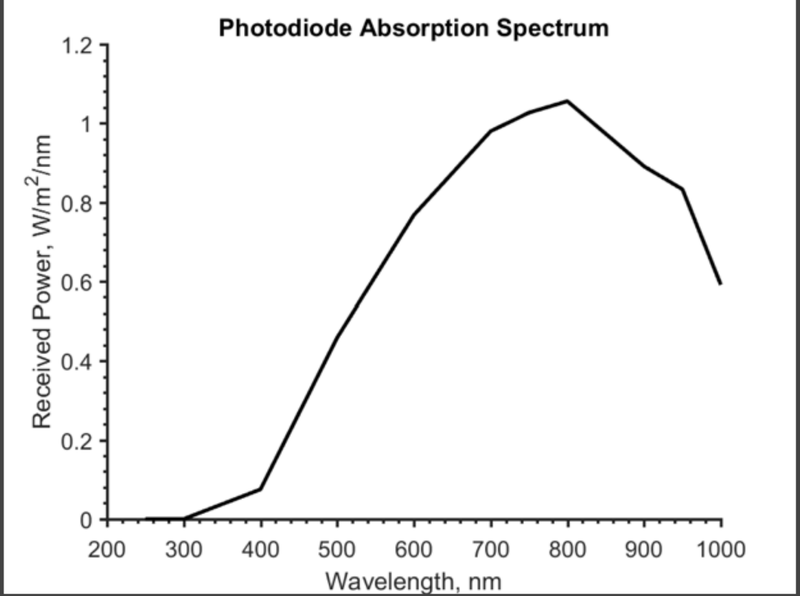


Fig. 6 - Relative Spectral Sensitivity vs. Wavelength

Sun Knowledge - Accuracy



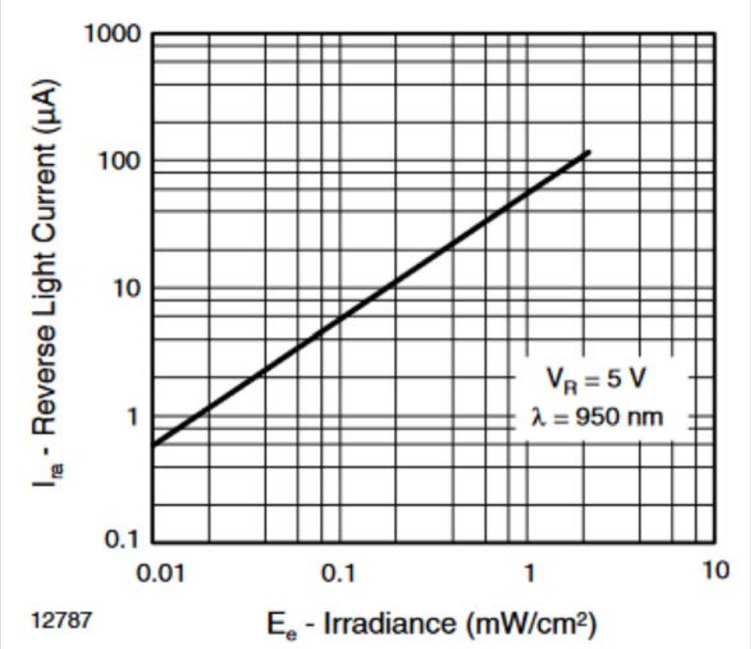
Multiply solar irradiance spectrum and photodiode relative spectral sensitivity at each wavelength
Result is photodiode power per area across the full spectrum

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**

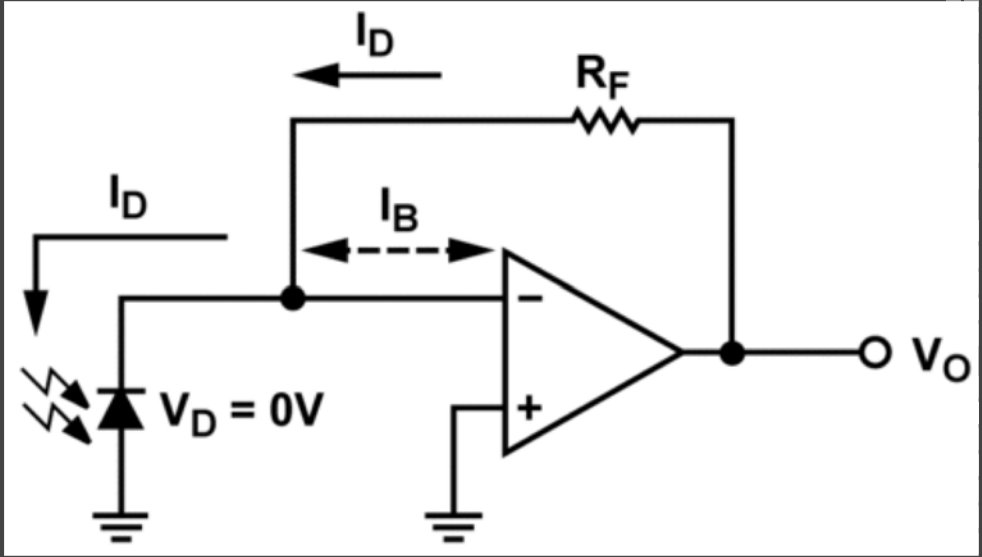


Sun Knowledge - Accuracy

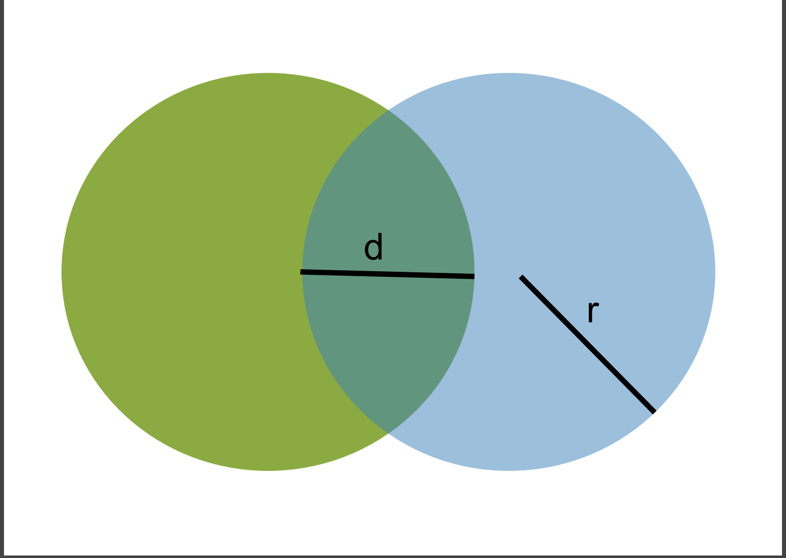
Implement a transimpedance amplifier to boost the signal and convert current to voltage.

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

Output voltage is **within microcontroller range**



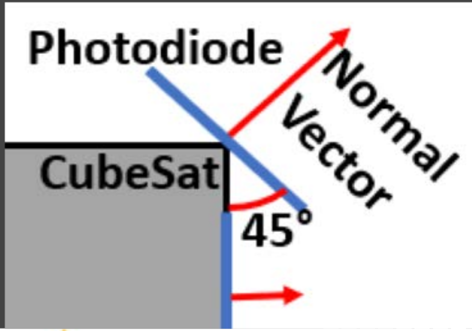
Photodiode Covers – Exposed Area

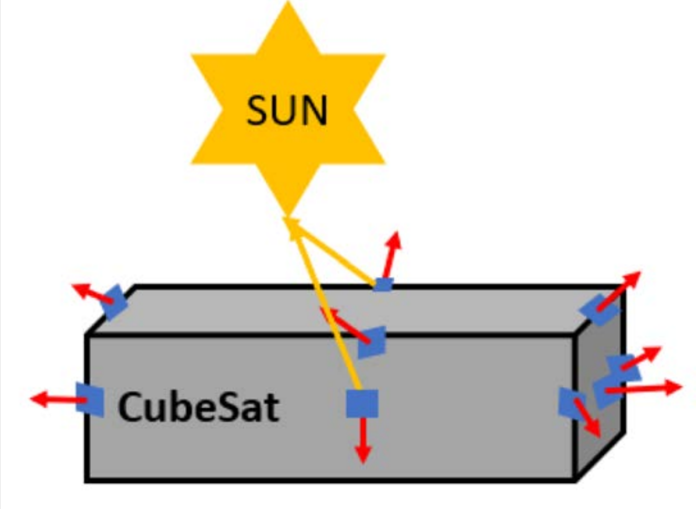


$$A = 2R^2 \cos^{-1}\left(\frac{d}{2R}\right) - \frac{1}{2} d \sqrt{4R^2 - d^2}$$

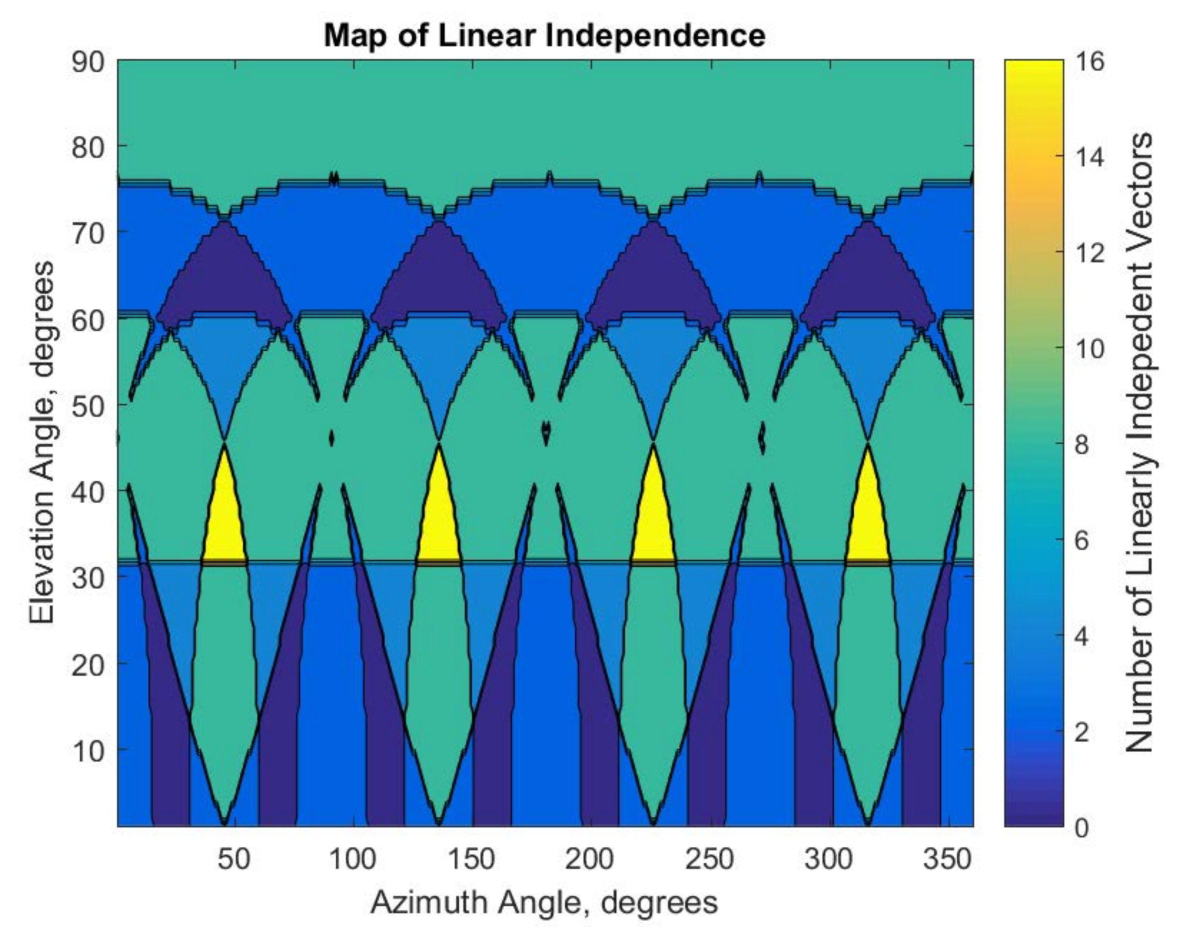
Sun Sensor Design

- 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



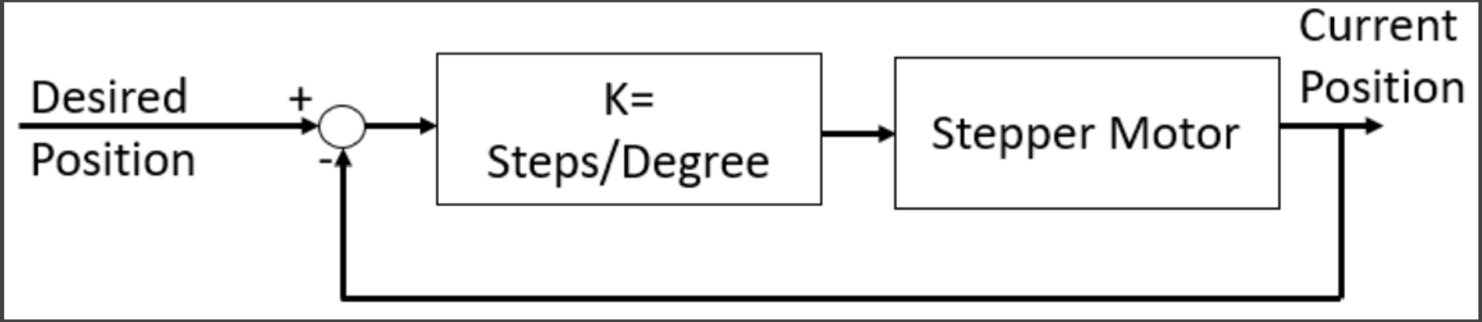
ARS Software: Control Loop Design

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

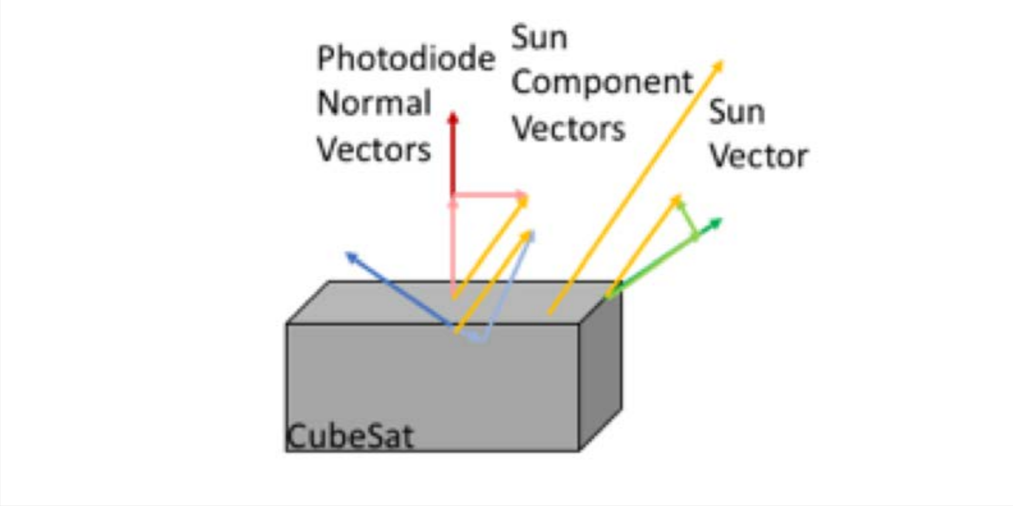
The Sun

1 vector

From 3 diodes

3 vectors

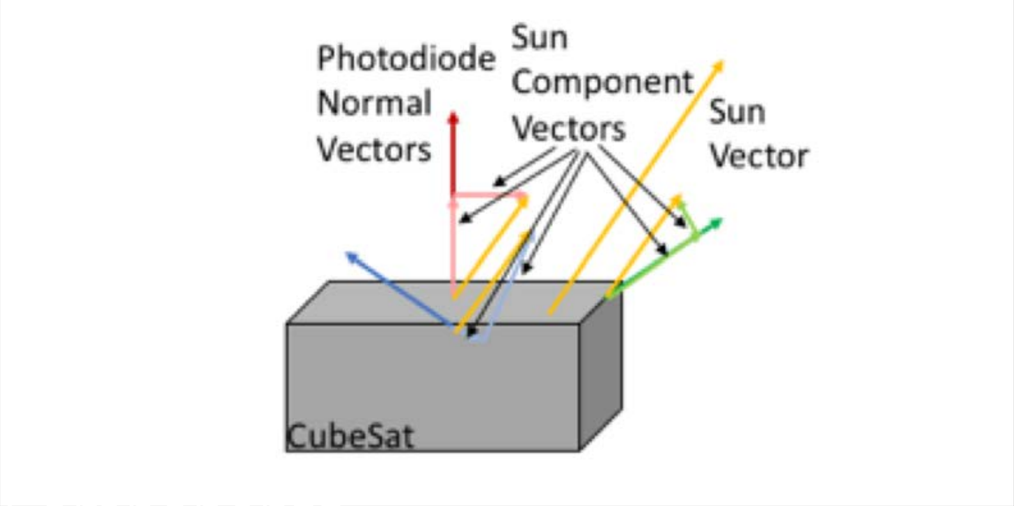
3 angles



Determining the Sun Vector

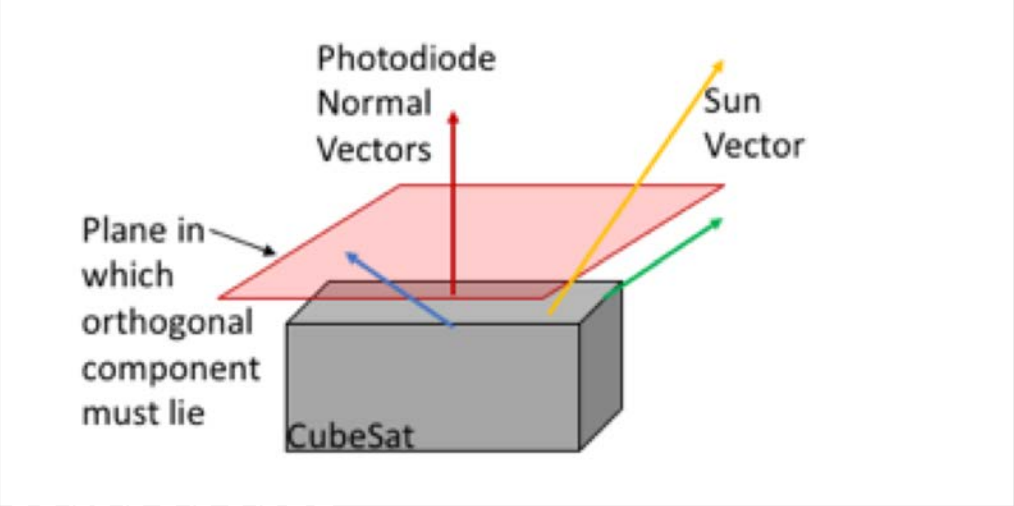
The Sun
- 1 vector

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



Determining the Sun Vector

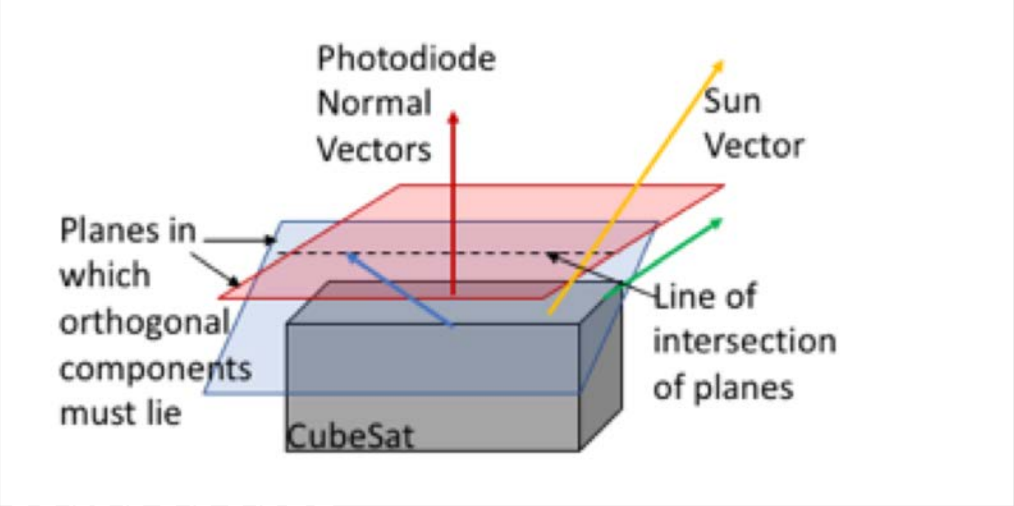
- The Sun
  - 1 vector
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector components
  - Define 1 plane



Determining the Sun Vector

The Sun
- 1 vector

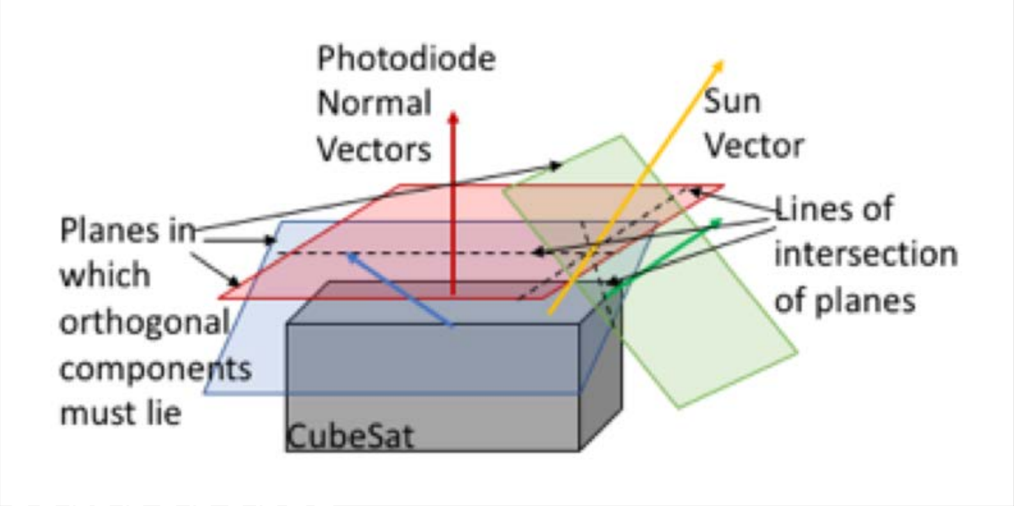
From 3 diodes
- 3 vectors
- 3 angles
- 3 Sun vector components
- Define 2 planes



Determining the Sun Vector

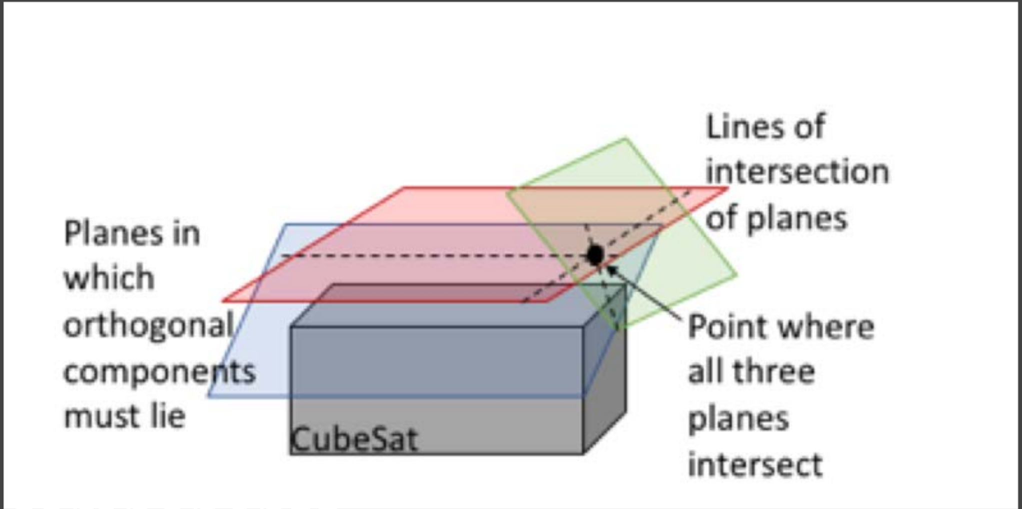
The Sun
- 1 vector

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



Determining the Sun Vector

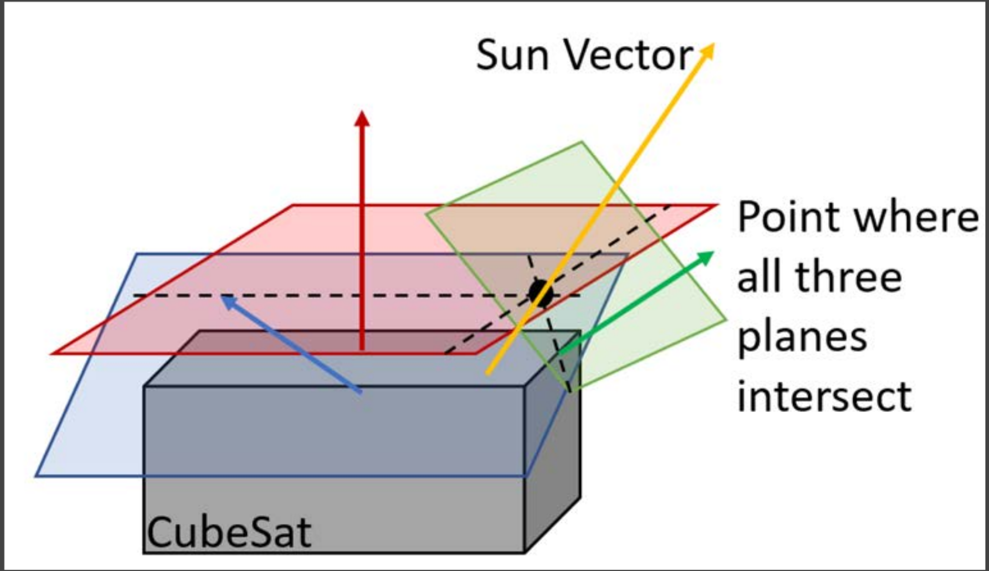
- The Sun
  - 1 vector
- From 3 diodes
  - 3 vectors
  - 3 angles
  - 3 Sun vector components
  - Define 3 planes
  - Intersection point



Determining the Sun Vector

The Sun
    1 vector

From 3 diodes
    3 vectors
    3 angles
    3 planes
    Intersection point



Sun Vector

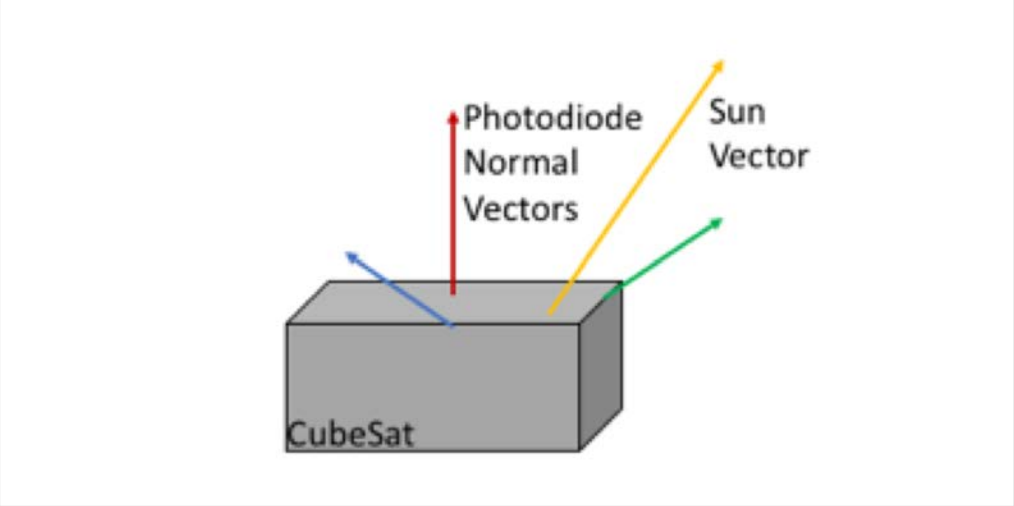
Determining the Sun Vector

The Sun

1 vector

From 3 diodes

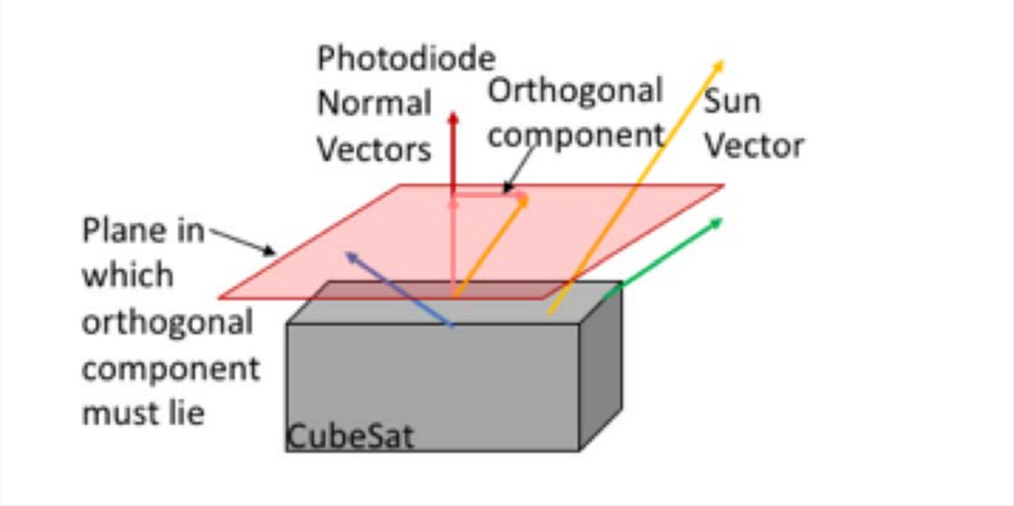
3 vectors



Determining the Sun Vector

The Sun
  1 vector

From 3 diodes
  3 vectors
  3 angles
  3 planes



Equations for Intersection

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

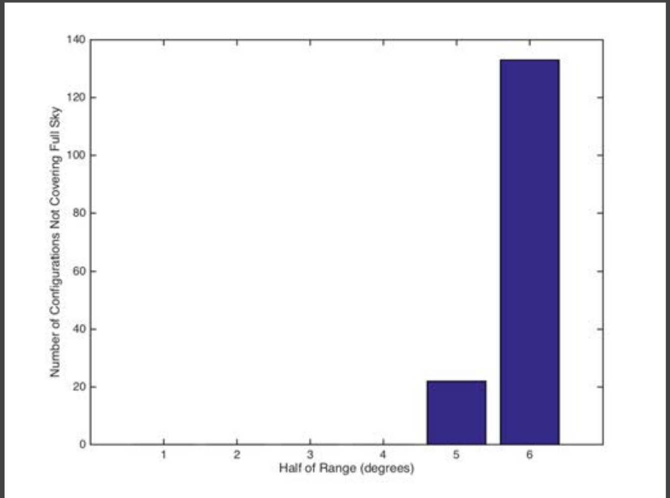
$$\hat{Z}_{21}\left(X - \hat{Z}_{11}\cos(\alpha_2)\right) + \hat{Z}_{22}\left(Y - \hat{Z}_{22}\cos(\alpha_2)\right) + \hat{Z}_{23}\left(Z - \hat{Z}_{23}\cos(\alpha_2)\right) = 0$$

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

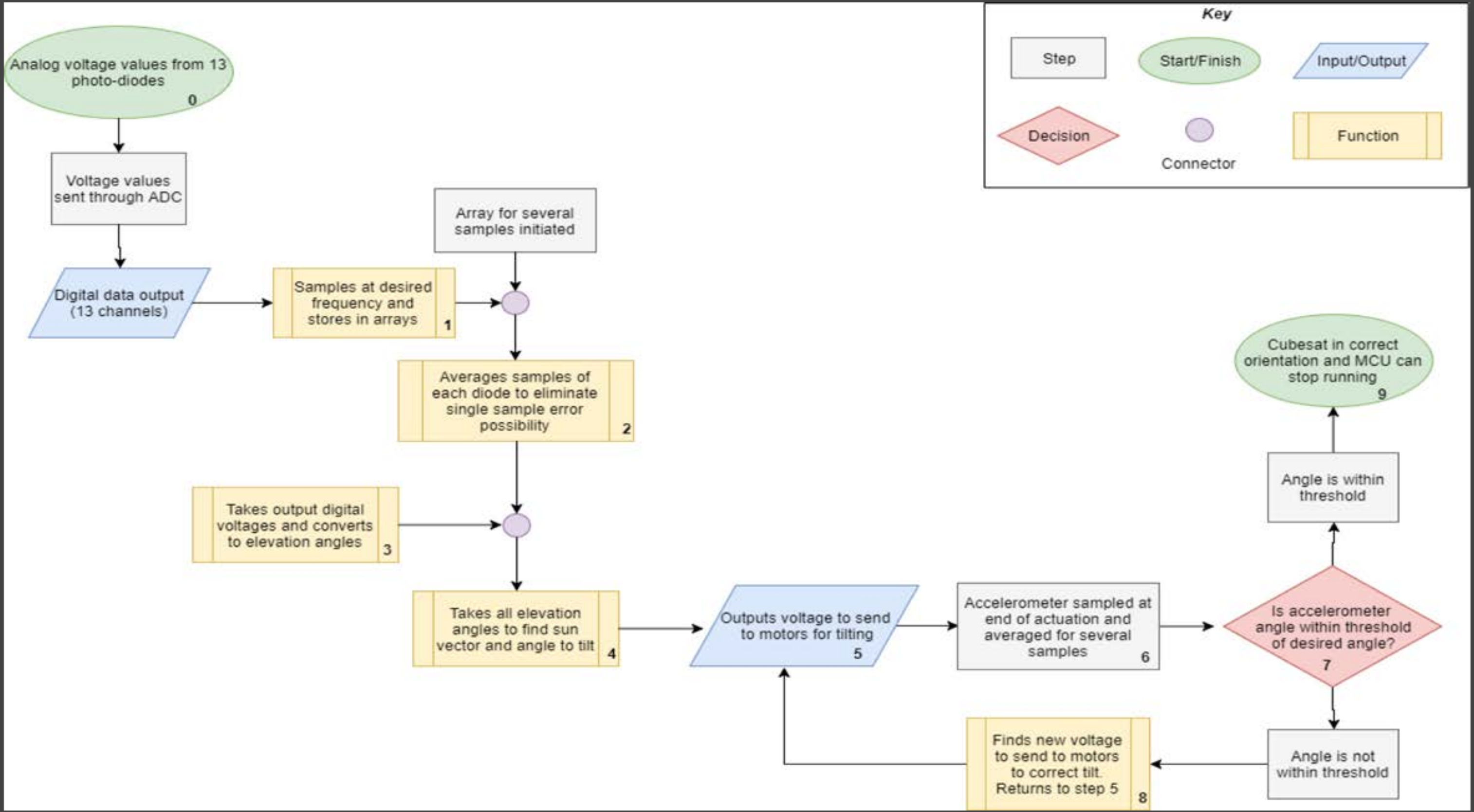
$\hat{Z}_{xy}$ is the xth photodiode vector yth component
α_x is the xth photodiode sun angle
X,Y,Z are the body components of the sun vector

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

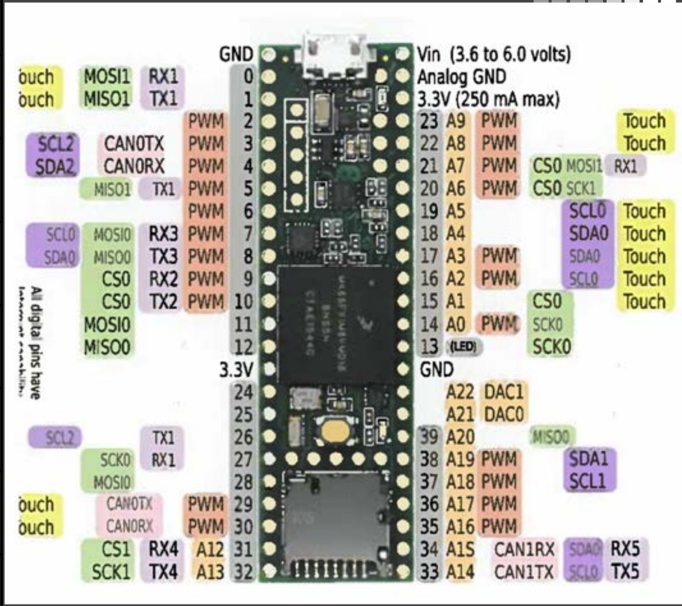


ARS Software



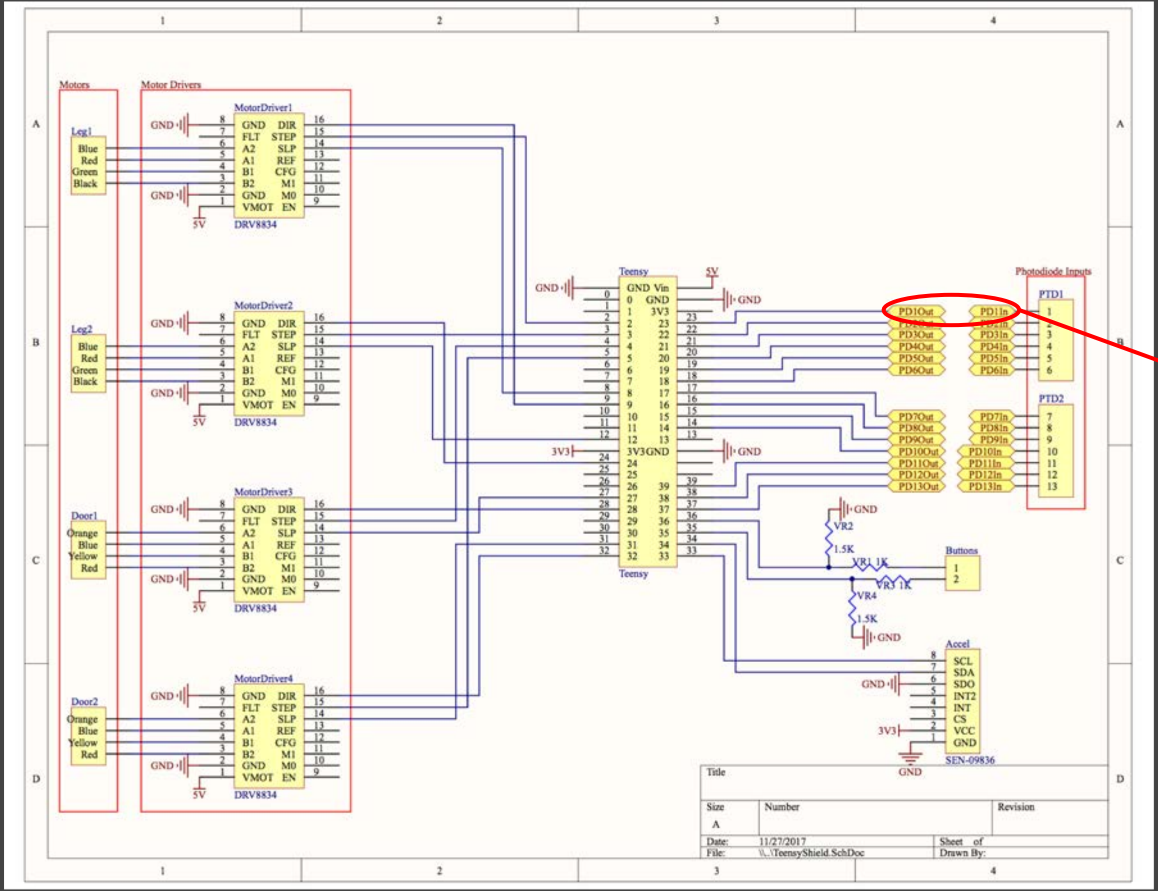
ARS Microcontroller

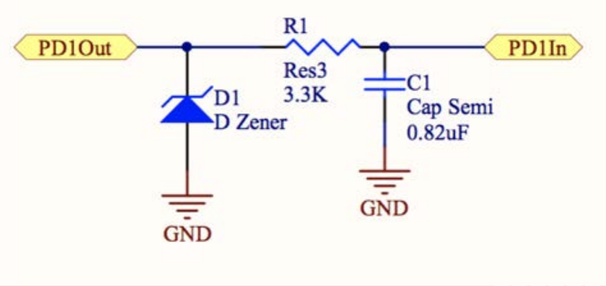
Component	Type/# of Component Pins	Pins on Teensy
Motor Drivers (x4)	Digital/4 (x4)*	6-12 and 24-32
	PWM/1 (x4)	2-5
Buttons (x2)	Digital/1 (x2)	35-36
Accelerometer	SPI/2	33-34
Photodiodes (x13)	Analog/1 (x13)	14-23
Door Command	Digital/1	0
Data Transmit	Serial/1	USB



* 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

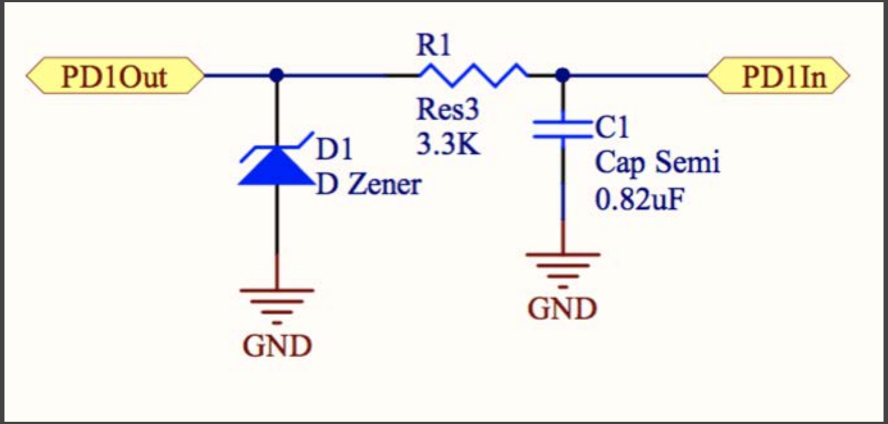




ARS Photodiode Noise

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.



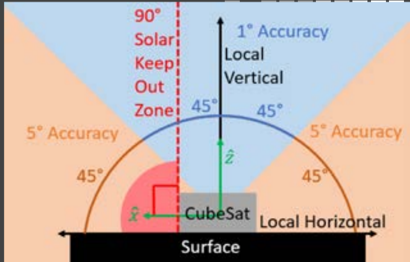
ARS Requirements Development

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.



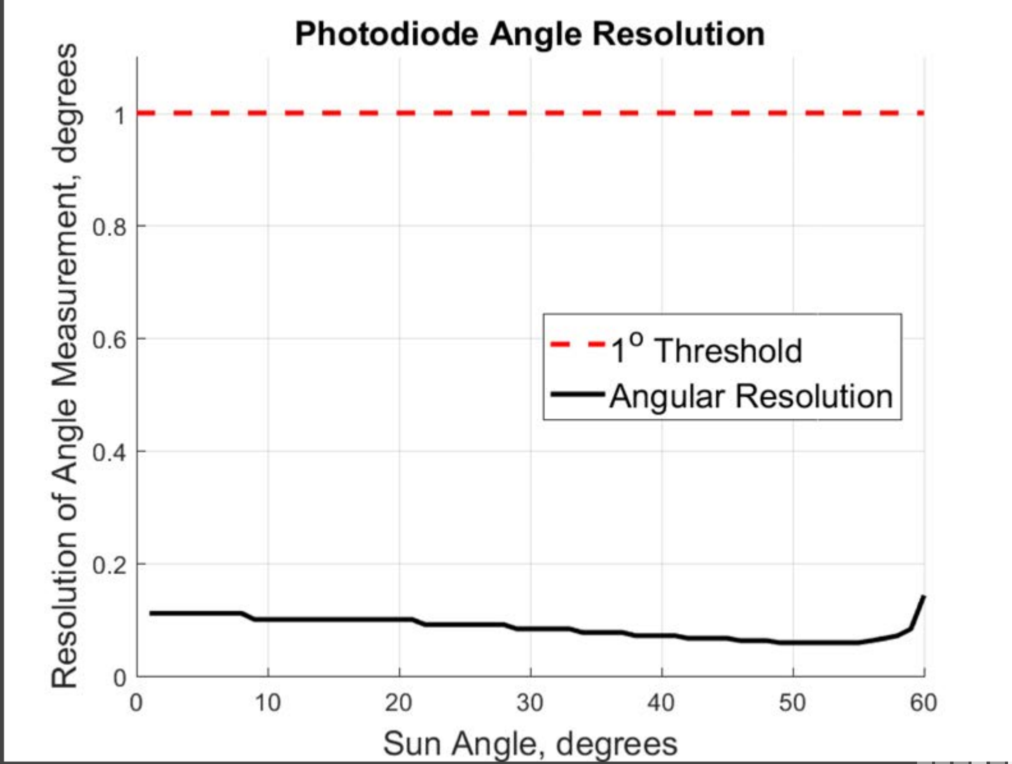
ARS Photodiode Resolution

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

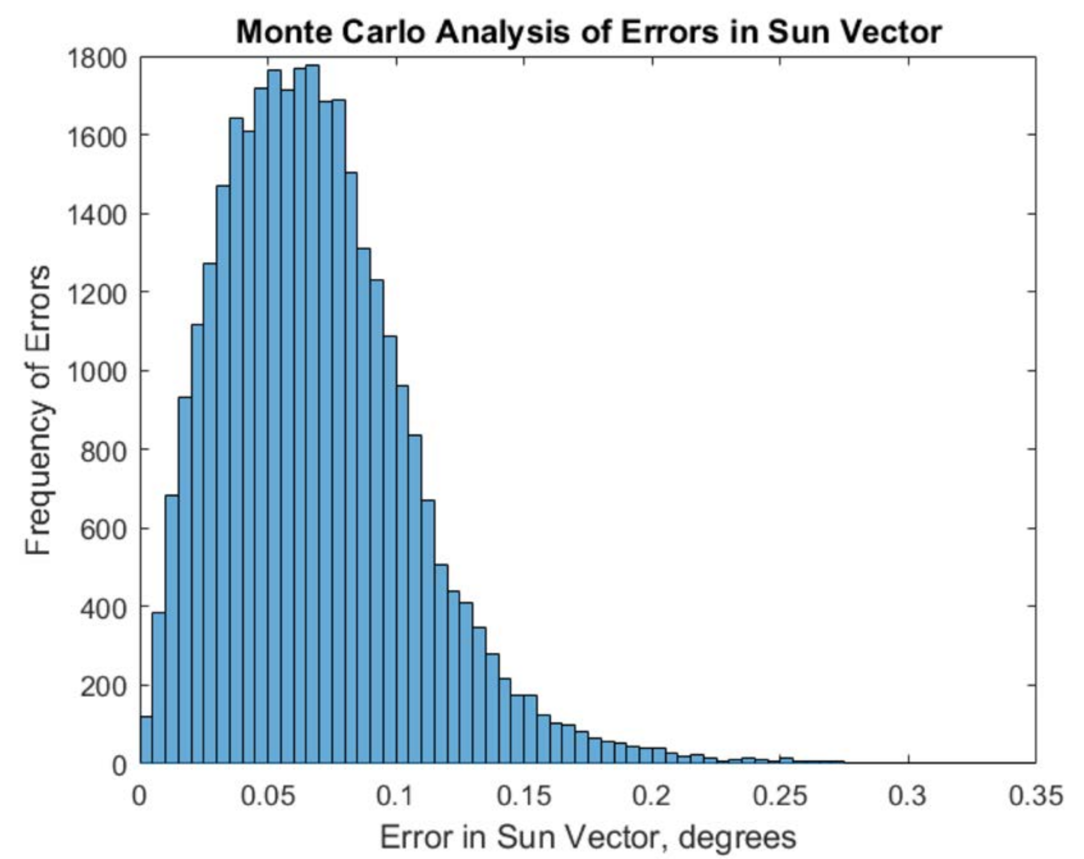
Maximum error in sun vector is 0.35°

Worst Errors 0.35° < 1°

Requirement 3.2.2 satisfied

However, margin is a concern

Manufacturing tolerances could push above 1°



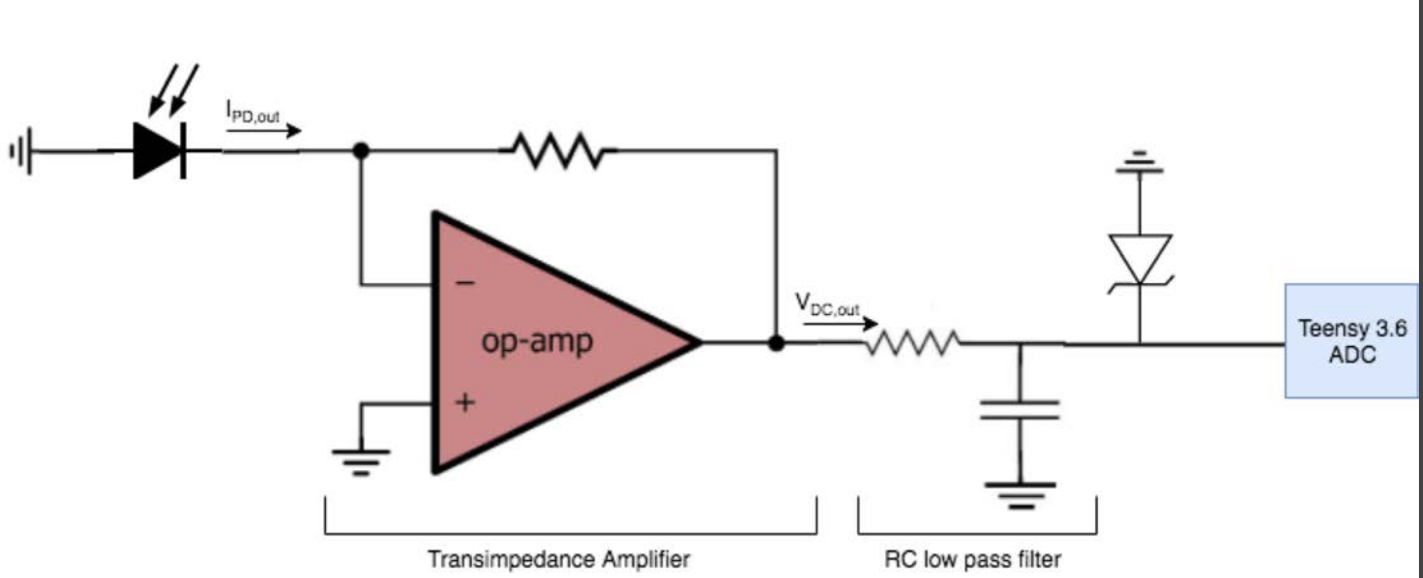
ARS Photodiode Signal Processing

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)

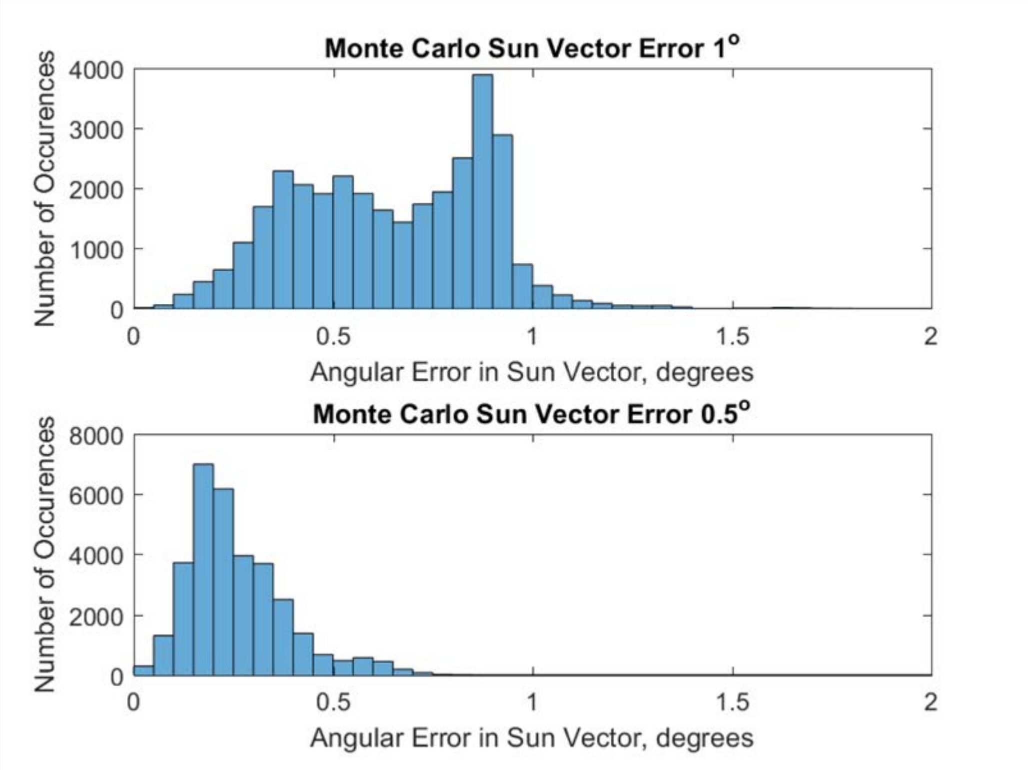


Off-Nominal Design Case

Photodiodes won't be mounted perfectly

Knowing position improves accuracy

ARS component level testing will allow us to find these errors



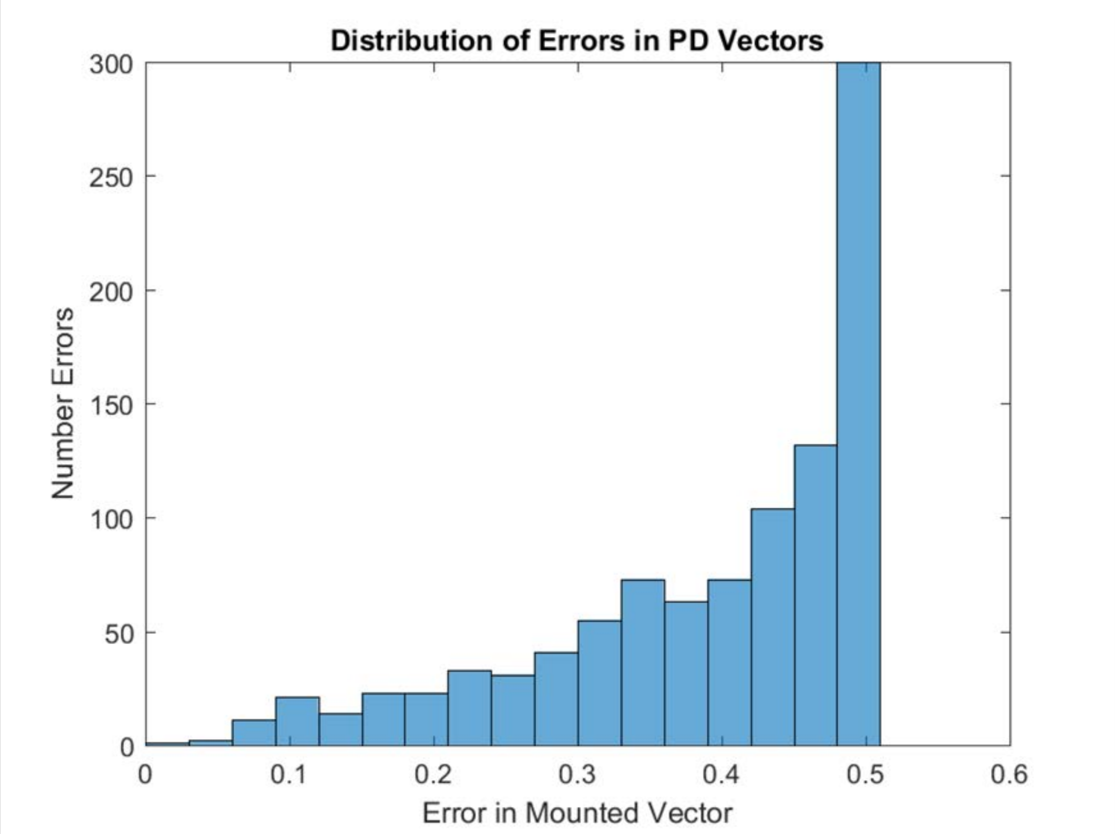
Worst Errors 0.75° < 1°

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

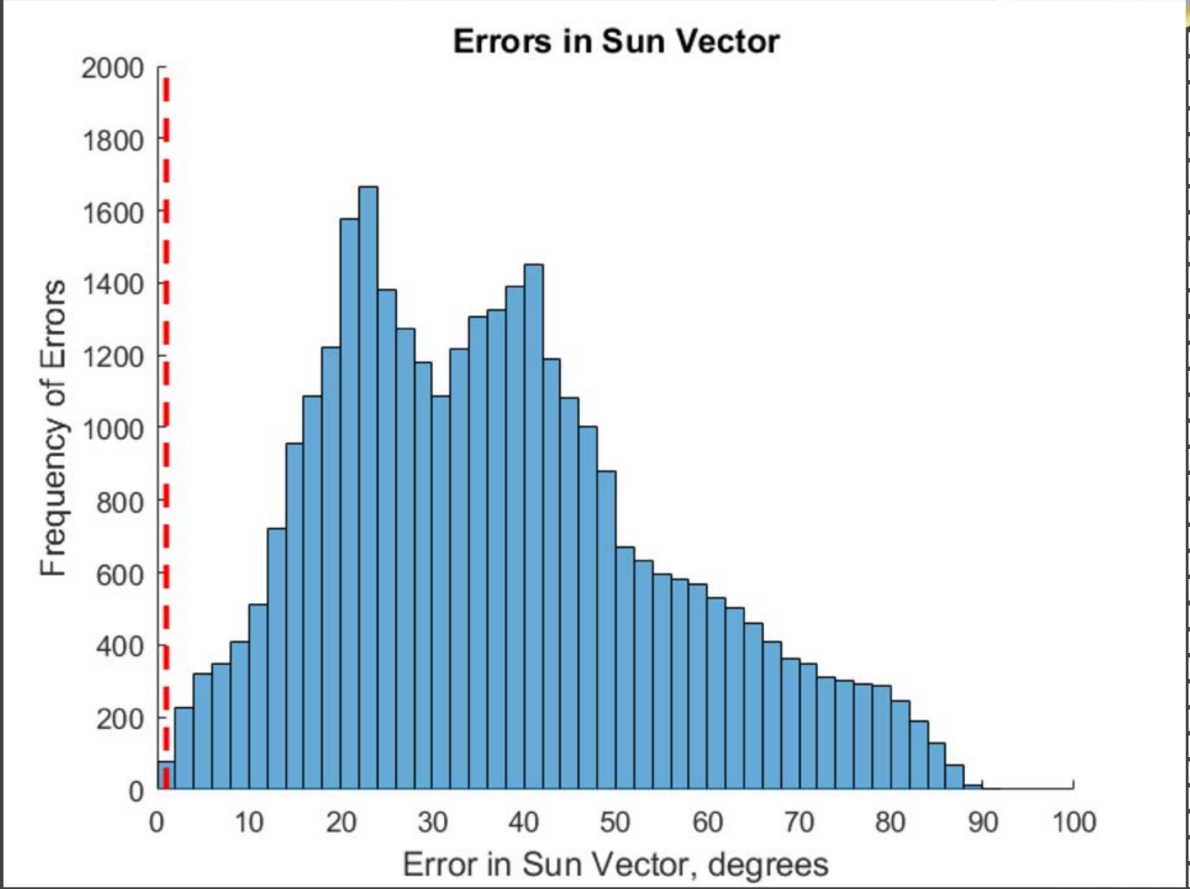
We are having issues correctly modeling the error from photodiode covers

Minute (0.0005 mm) changes in manufacturing tolerances cause outrageous errors

- Sun angle
- Photodiode Voltage

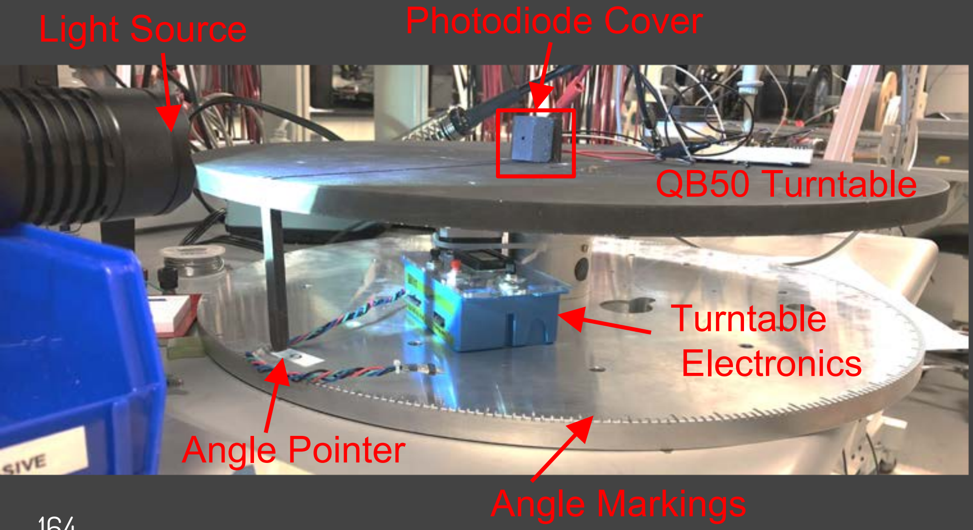
Two Options:

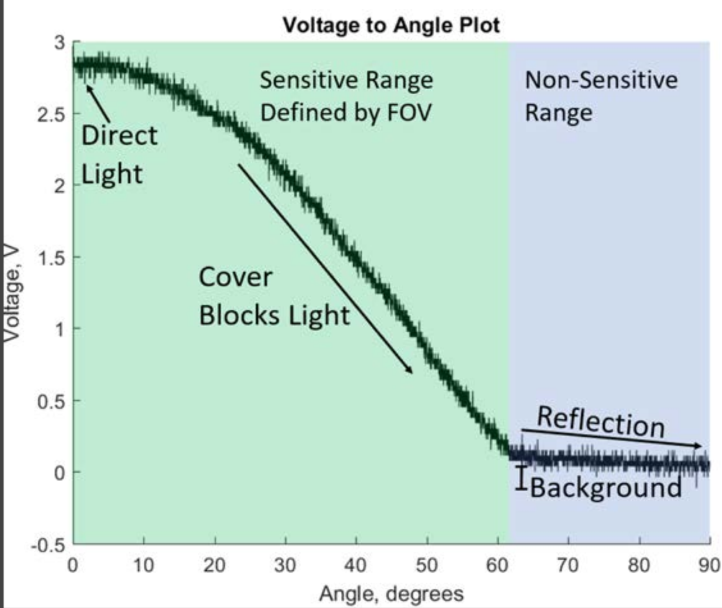
- Off ramp to which side is sunnier
- Calibrate out photodiode cover error



Photodiode Calibration

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





ARS Sensors Status

- Completed
  - Test PCBs ordered and verifying
  - Test cases printed
- Future Work
  - Print all cases (Easy)
  - Order all PCB copies and mount components (Easy, time consuming)
  - Calibrate PCB and cover sets (Difficult, bulk of ARS work)
  - Integrate with CubeSat (Medium)
  - Cable routing (Unknown)