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

Dust BUSTER

<u>B</u>oulder <u>U</u>nmanned <u>S</u>ensor for <u>T</u>ransport <u>E</u>vents and <u>R</u>epositioner

Preliminary Design Review

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Project Overview

Project Overview | Baseline Design | Feasibility Study | Summary

Project Motivation

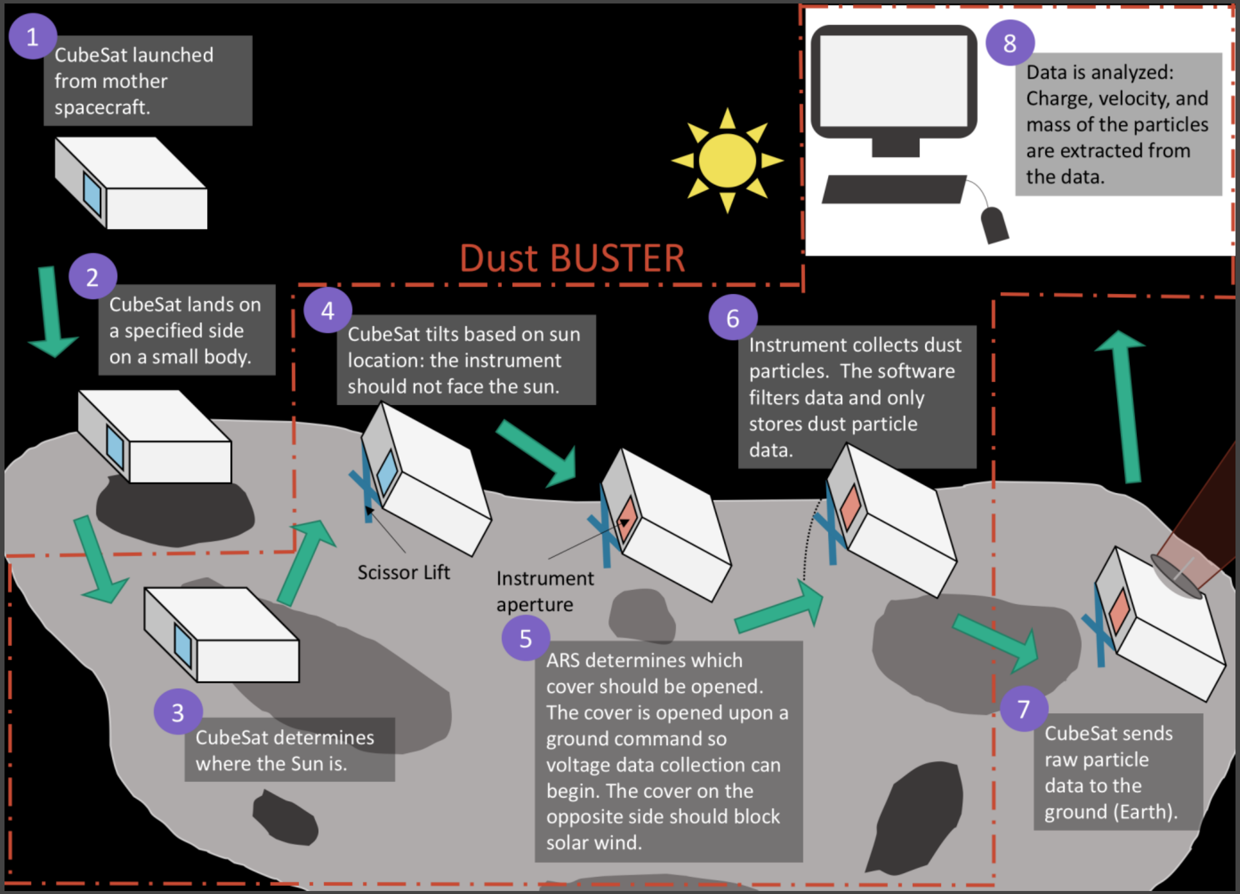
- Dr. Wang's research at LASP suggests that charged particles could be lifted by their Coulomb force
  - Dust transport events: micron-sized dust particles are charged by various sources in space and ejected from the surface of low-mass bodies
  - This has been tested in a lab setting but never in a low-gravity environment
- A dust instrument to collect data on these particles currently exists but is too large for a space application

Data on charged dust 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

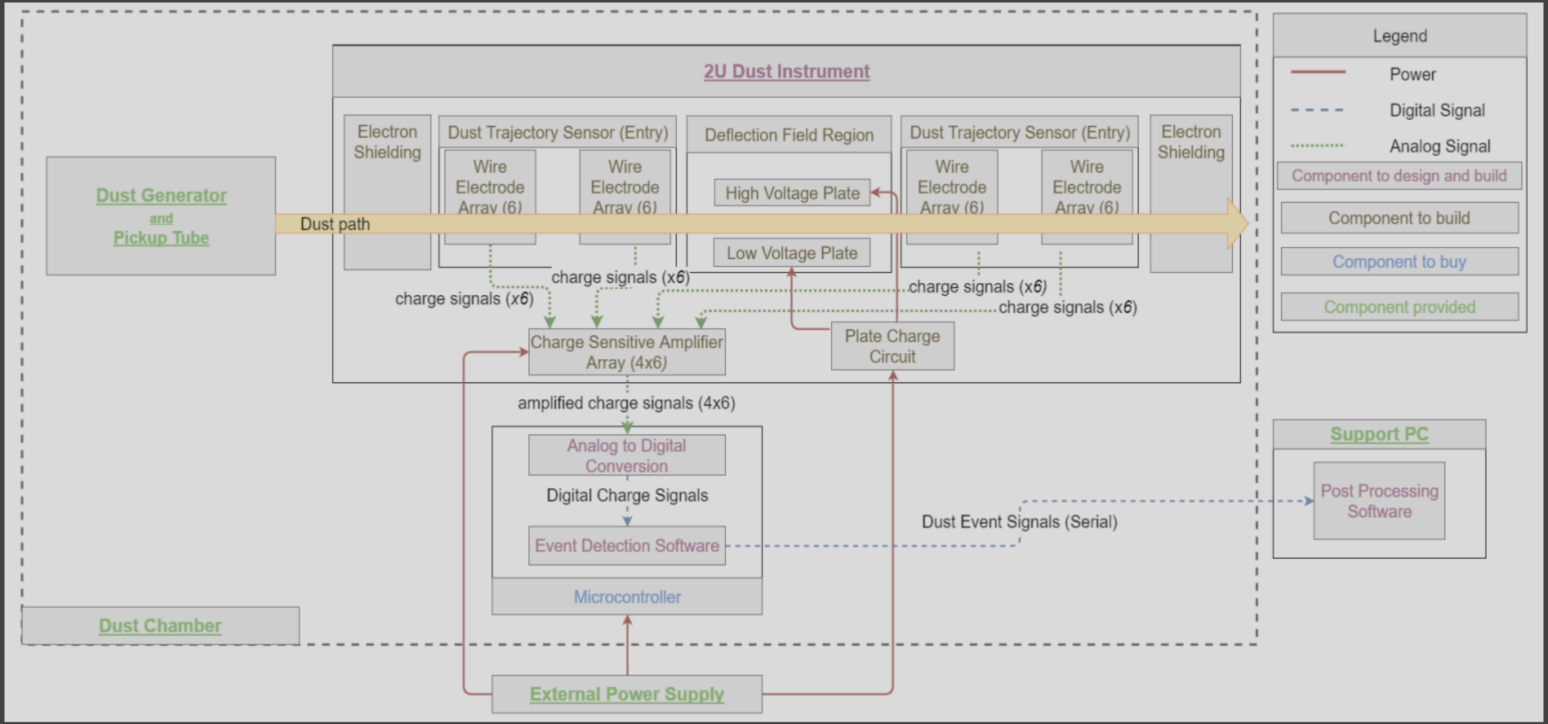
Overall Mission ConOps



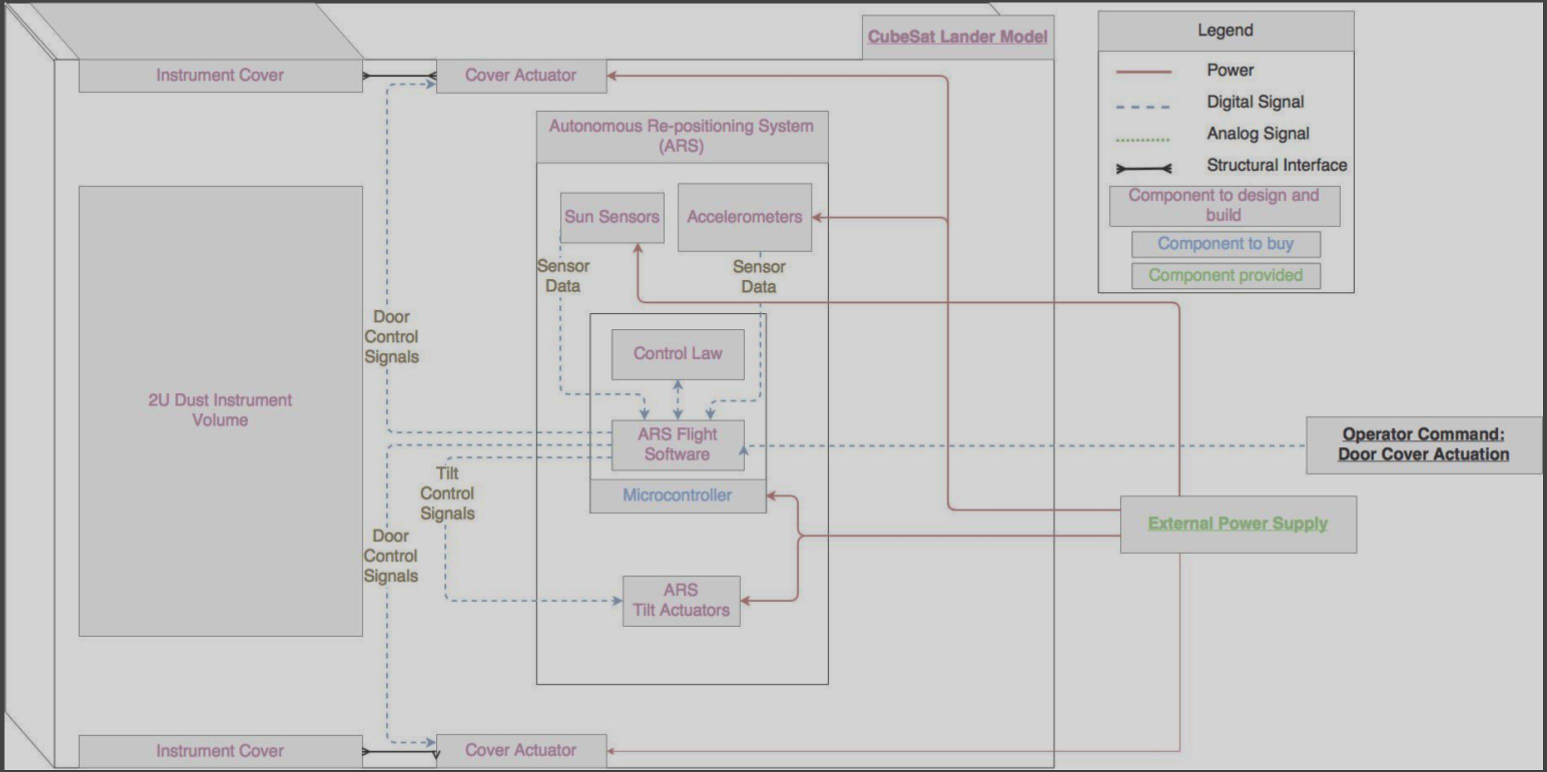
Functional Requirements

FR 1	The CubeSat model shall contain the 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 ARS and mechanisms shall open the instrument door that is pointing away from the sun.
FR 4	The ARS and 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 repositioning systems.
FR 6	The software shall be capable of data processing, detecting dust events, and running ARS algorithms.

Instrument Functional Block Diagram

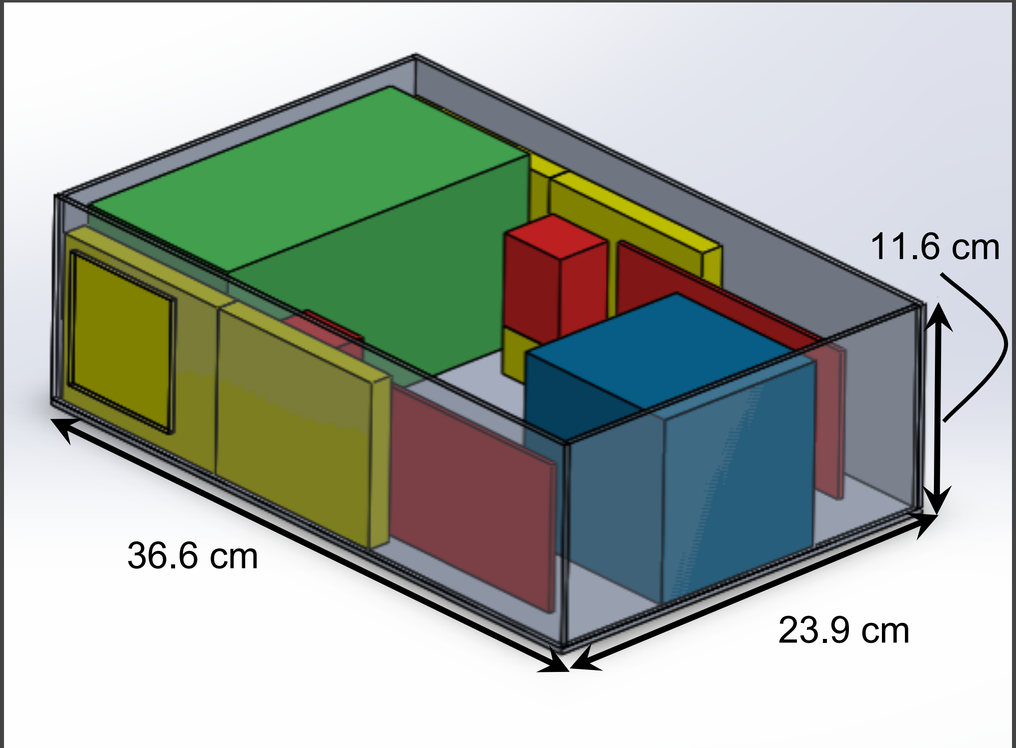


ARS Functional Block Diagram

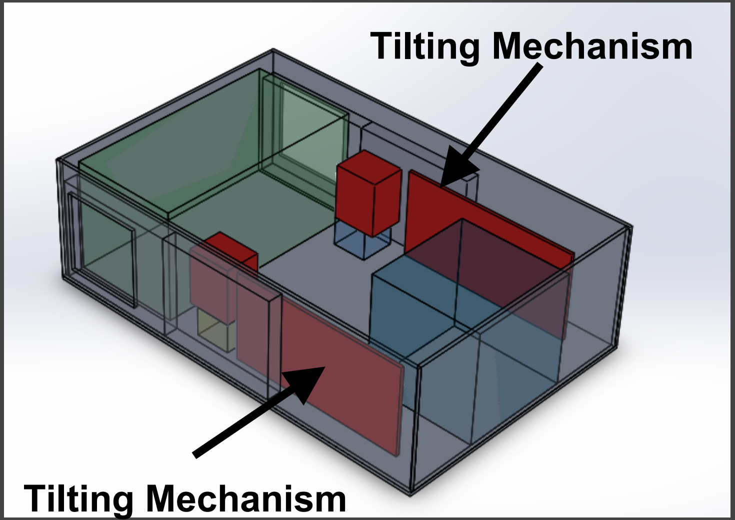


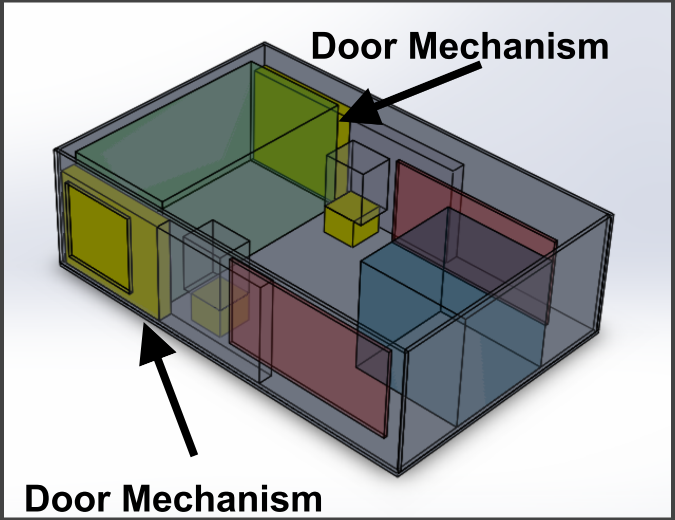
Baseline Design

Project Overview | Baseline Design | Feasibility Study | Summary



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





ARS Baseline Design

Determine Sun location and tilt angle

Mechanically tilt and open dust cover doors

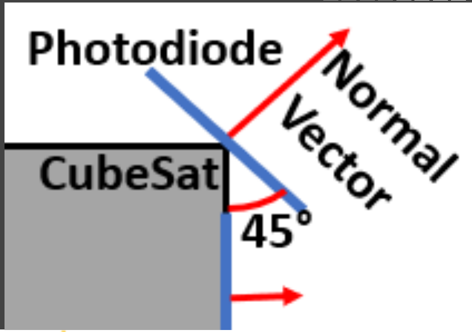
Sun Sensor Baseline Design

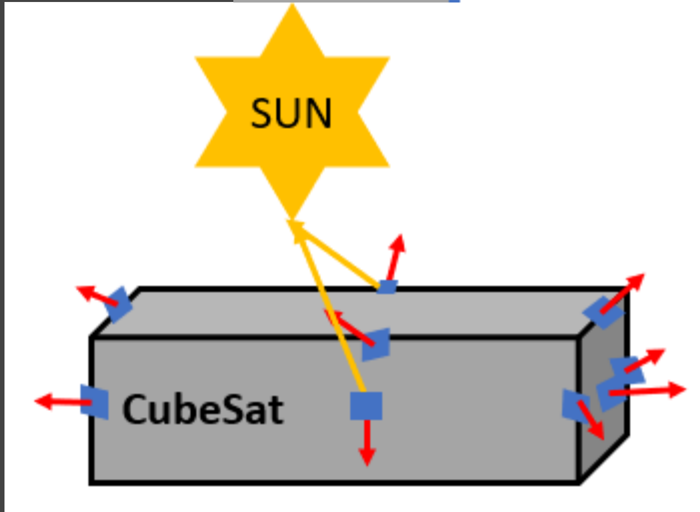
Why do we need the Sun position?

- 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





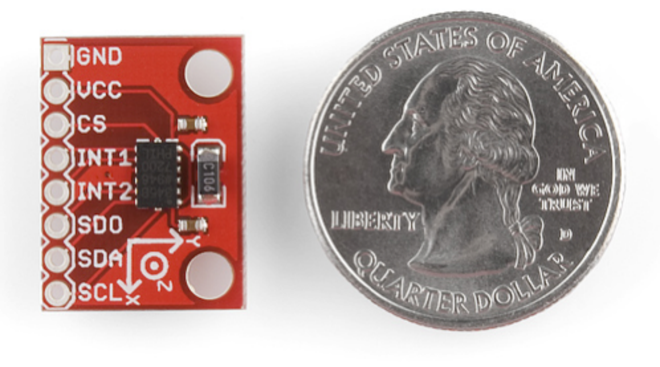
Tilt Sensor Baseline Design

Why do we need tilt knowledge?

- Need to know how far we have tilted **<u>independent</u>** of ARS commanded position

How? Accelerometer: ADXL345 SparkFun

- Specifically built to measure static acceleration of gravity in tilt-sensing applications
- 13-bit resolution for 2 Gs
- High resolution: 4 mG
- **Angular accuracy of 0.1°**



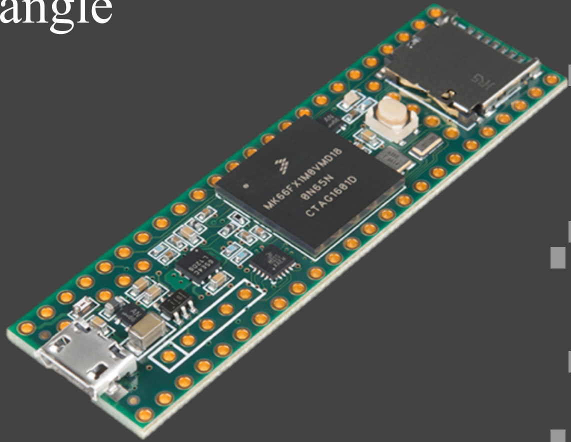
ARS Microcontroller Baseline Design

Why do we need an ARS Microcontroller?

- Process photodiode and accelerometer data
- Determine location of Sun and CubeSat tilt angle
- Determine how much to actuate CubeSat
- Command motors to actuate CubeSat
- Process command to open door

How? Teensy 3.6

- Arduino-compatible
- 25 analog inputs (photodiodes)
- 22 PWM outputs (stepper motor and servo)
- SPI and I2C capability (accelerometer)



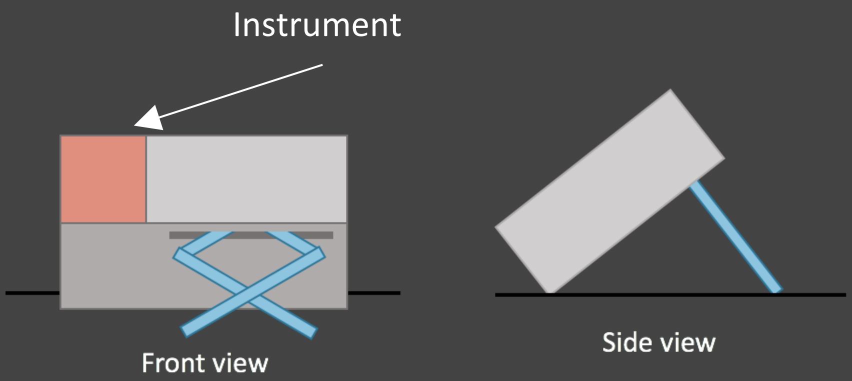
Tilting Mechanism Baseline Design

Why do we need to tilt?

- The CubeSat needs to tilt up to 45° for the instrument to maximize dust collection capability
- Needs to tilt in 1° increments to reach the maximum angle that does not cause sunlight exposure

How? Scissor Lift

- 2 scissor lifts
- 2 cm from edge to leave room for doors



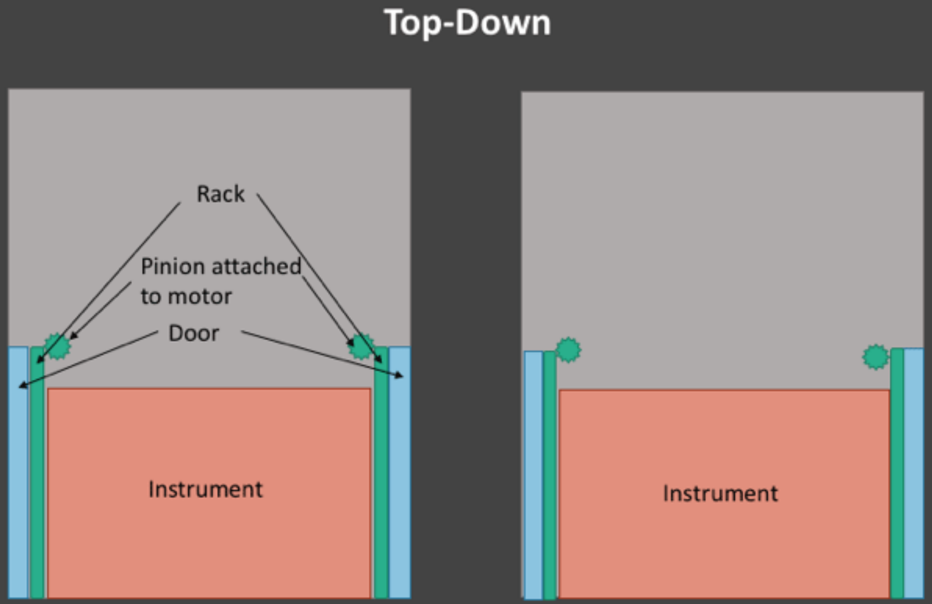
Dust Cover Baseline Design

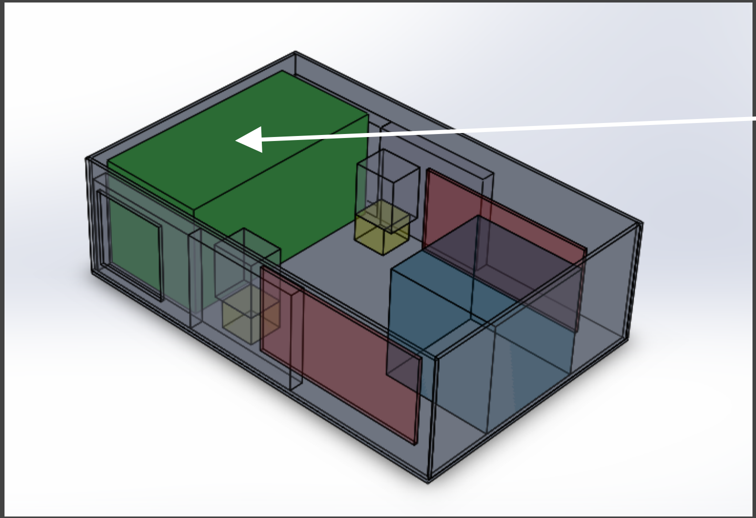
Why do we need a dust cover?

- Protects the instrument from the solar wind
- Need to open the door which is not in sunlight based on ARS sensor knowledge

How? Rack & Pinion

- Motor turns pinion
- Pinion moves rack
- Door slides back





Instrument Baseline Design

Collecting and processing dust data

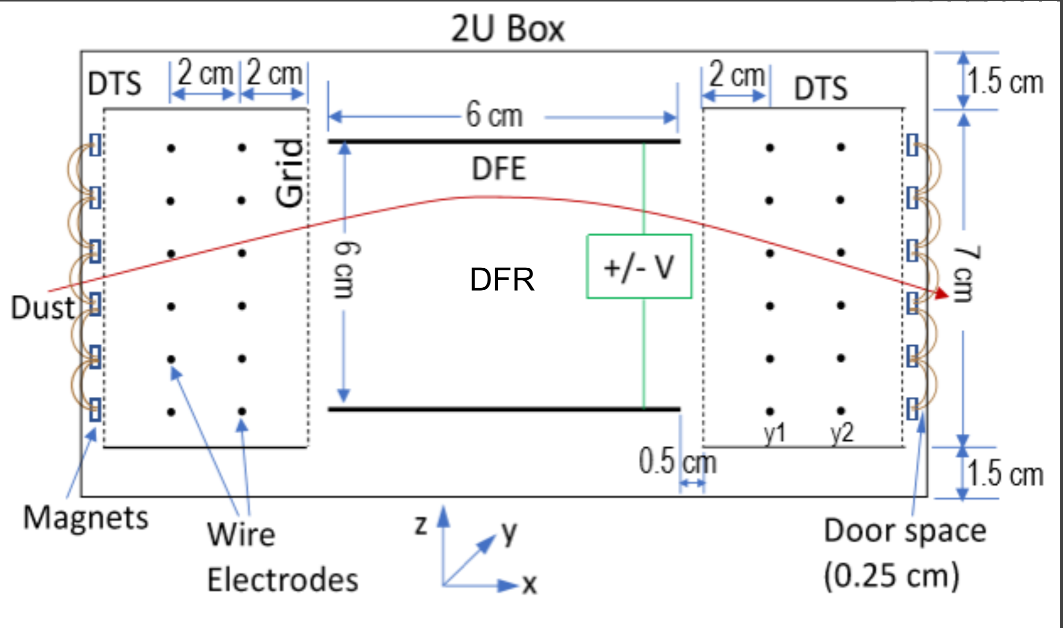
Dust Instrument Design

Why do we need an instrument?

- To collect dust data!

How do we collect dust data?

- Two Dust Trajectory Sensors (DTS) containing wire electrode arrays
- Two Deflection Field Electrodes (DFE) on each side of the Deflection Field Region (DFR) to deflect the charged dust particles
- A magnetic array in front of each chamber entrance
- Confined to a 2U volume (20x10x11.3cm)



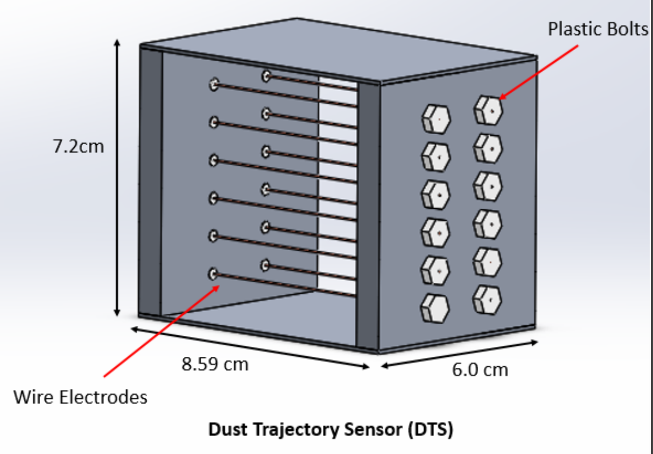
Wire Electrode Tension Mechanism

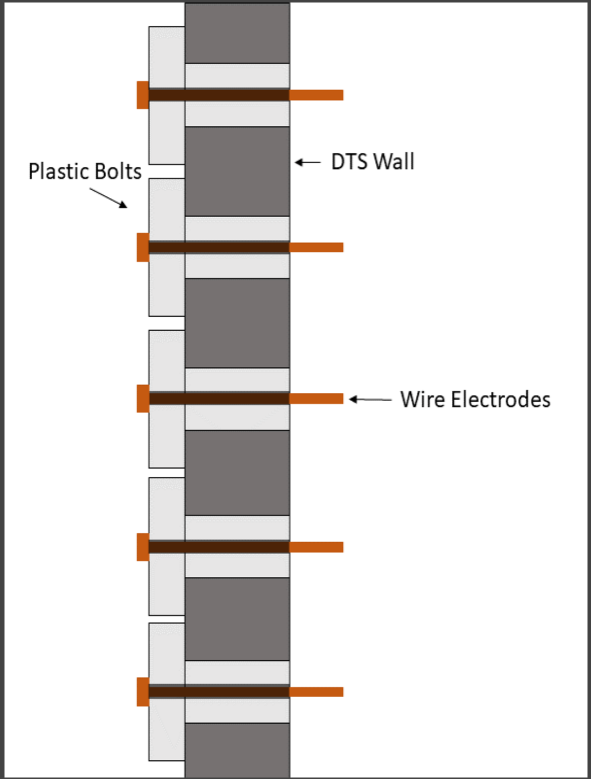
Why do we need tension in the wires?

- Maintain instrument accuracy

How? Plastic Blots

- Electrically insulating plastic bolts screw into wall of DTS
- Hole in bolt for the wire electrode to pass through





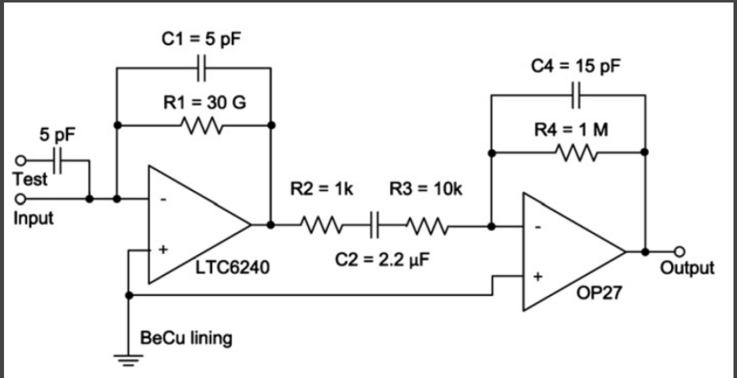
Charge Sensitive Amplifier (CSA) Design

Why do we need an amplifier?

- Induced charge on wire electrodes is very small (~100 fC)
- Transform induced charge into voltage signals

How? Customer defined CSA

- The first op-amp is a charge sensitive preamplifier that translates induced charge at the input to a voltage at its output
- The second stage is a standard op-amp voltage amplifier
- Low noise design
- Linear sensitivity



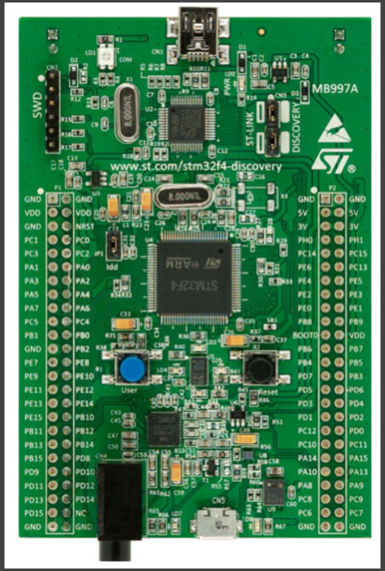
Instrument Processor and Event Trigger Baseline Design

Why do we need a processor and event trigger?

- Real-time sampling is required to determine when a dust event occurs, so only that data is saved

How?

- Microcontroller meets real-time requirements for 1 kHz sampling
- Integrated ADCs have 24 channels for 24 wire electrodes
- Trigger software compares expected signal to real signals to determine when an event takes place



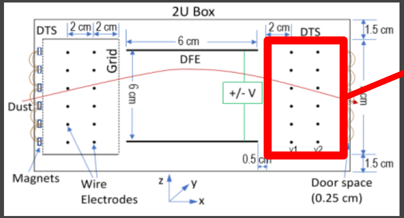
Post Processing Baseline Design

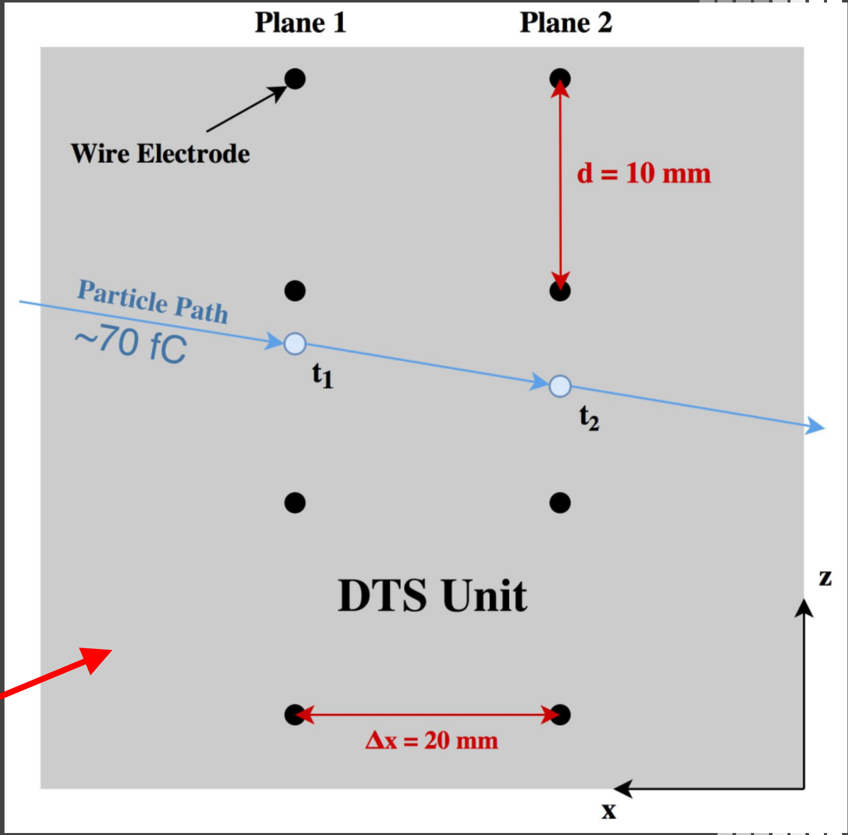
Why do we need post processing?

- Use raw voltage signals to extract the charge (Q), mass (m), and velocity (v) of an incident dust particle

How? MATLAB Code

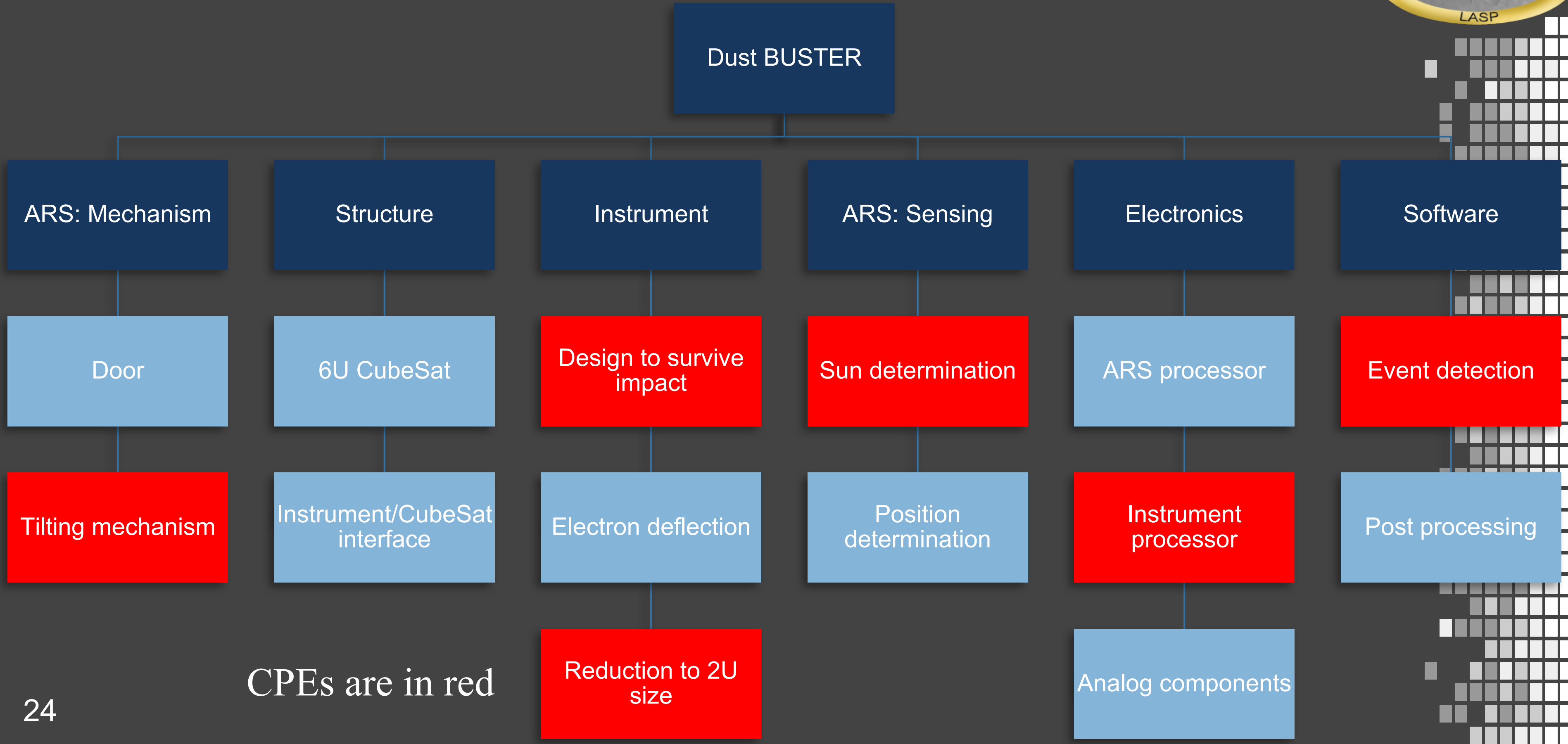
- Relative voltage outputs can be used to fully reconstruct trajectory in both space and time
- Using trajectory and known instrument parameters - Q, v, and m can be determined





Feasibility Studies

Critical Project Elements



CPEs are in red

Critical Project Elements

Critical Project Element	Description
Dust instrument miniaturization	Instrument is contained within a 2U volume
Surviving Impact	Tension mechanisms maintain tension after impact
Sun determination	Determine Sun position with 1° accuracy
Tilting mechanism	Tilt in 1° increments up to 45°
Instrument processor and event trigger	Sample 24 channels at 1 kHz and run event trigger

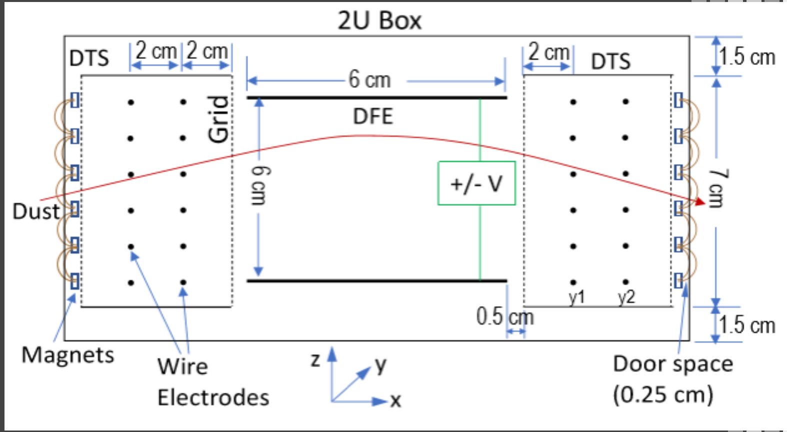
Dust Instrument Miniaturization

The instrument must be designed to fit within a 2U volume

Instrument Miniaturization

2.1: The detector portion of the instrument shall fit within a 2U volume (10 x 20 x 11.35 cm), not including the microcontroller.
1.1.1: The instrument shall have a maximum mass of 2.66 kg

- Customer has provided a schematic of the optimal design for 2U
- Design choices still needed:
  - Wire tension mechanism
  - Maximize wire electrode length to maximize instrument field of view

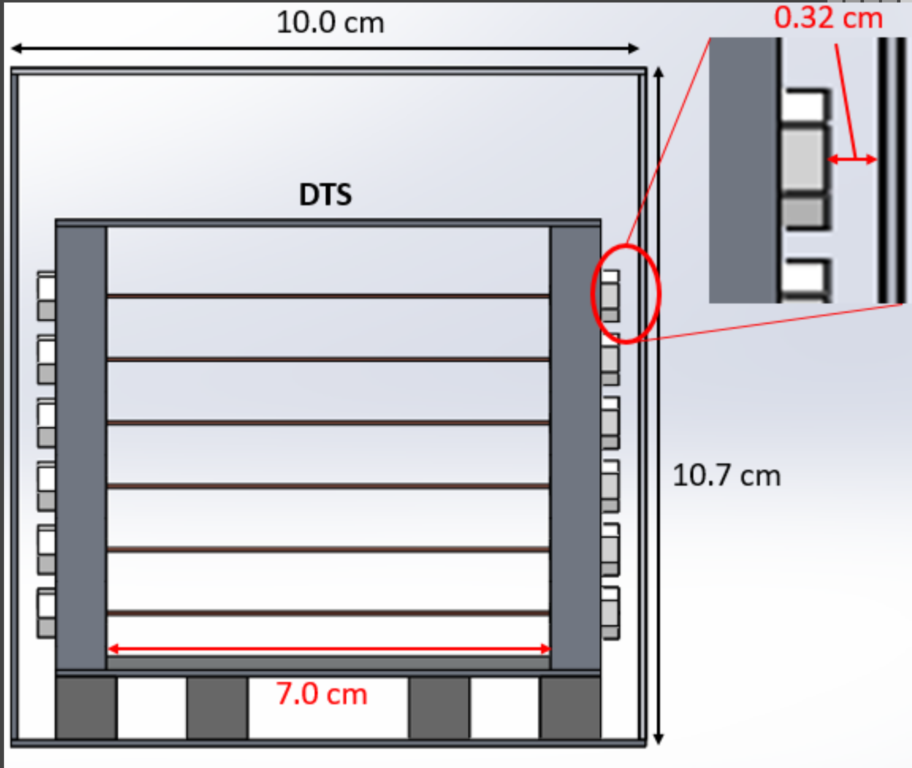


Instrument Size and Mass

- By model inspection the Dust Trajectory Sensor (DTS) can fit within the instrument 2U volume
- Thickness of DTS wall can be reduced to accommodate design
- Current mass is 735.5 g (not including magnetic arrays, bolts, and copper mesh)

Instrument Mass = 0.74 kg < 2.66 kg

Instrument contained in 2U → **Feasible**



Dust Instrument Side View

Surviving Impact

The wire electrodes must maintain tension after impact

Impact Design

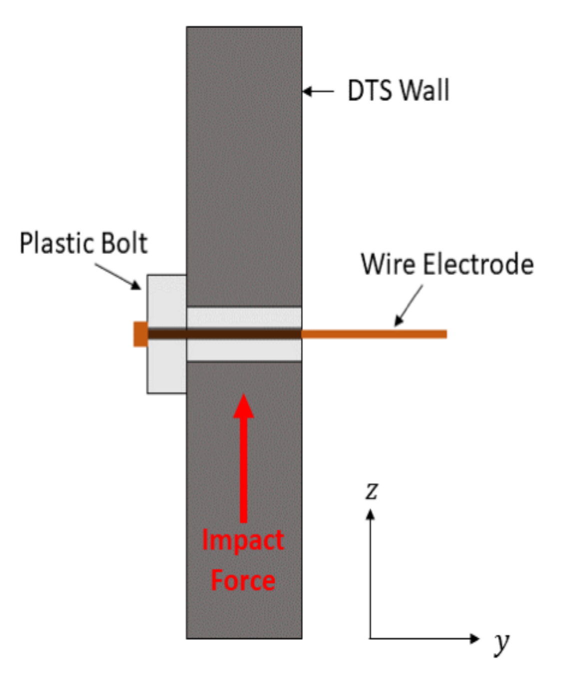
2.5 The wire electrodes shall remain taut - no more than 0.2mm deflection - after a 10 m/s collision on a regolith surface (1 cm to sub-micron sized particles).

- Plastic bolts maintain wire tension
- Preliminary bolt material choice is PEEK (Polyether ether ketone)
  - Shear Strength (τ) = 55.2 MPa = 55.2 N/mm^2
  - M4 Bolt Size - 4mm diameter

Max Shear Force = Shear Strength x Bolt Cross-sectional area

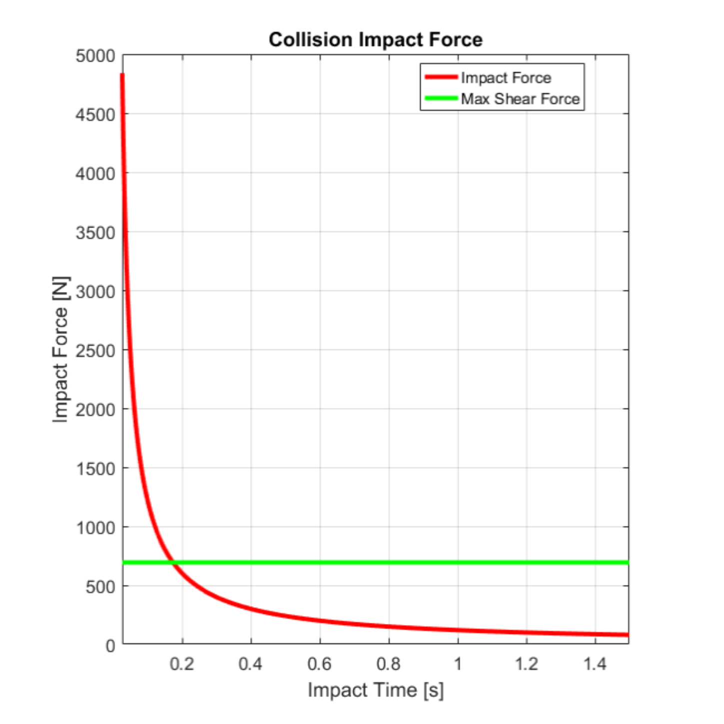
$$F_{shear} = \tau \times \pi \frac{d^2}{4} = 55.2 \times \pi \frac{4^2}{4}$$

→ **Max Shear Force = 694 N**



Impact Design

- Assumptions:
  - 10 m/s impact velocity
  - Perfectly inelastic collision (0 m/s final velocity)
  - CubeSat mass = 12 kg
  - Force distributed on CubeSat surface is different from force distributed on the dust instrument
- Preliminary impact time range defined as 0.05s to 1.5s
- Steps:
  - Calculate the impulse
  - Determine range of impact forces
  - Calculate the force per unit area
  - Translate the calculated pressure to a force on the dust instrument



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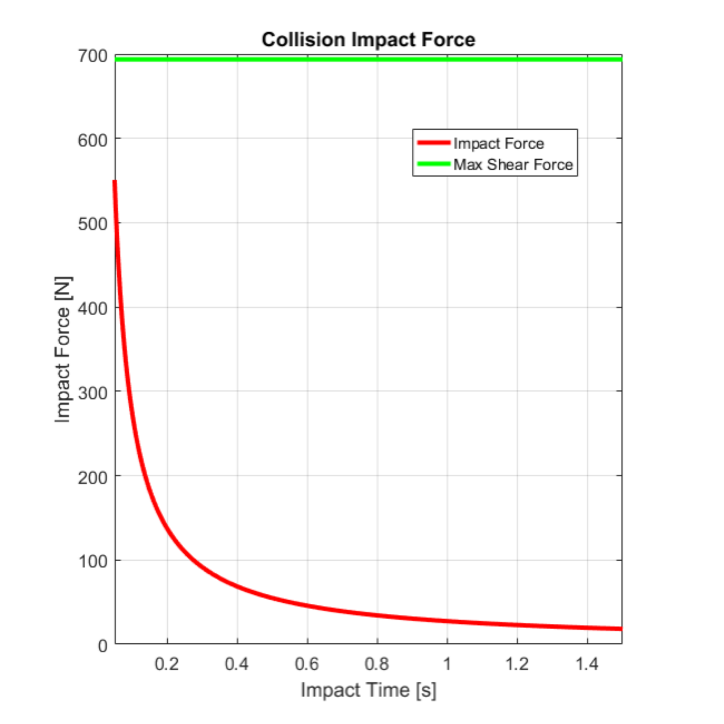


Feasibility Pending

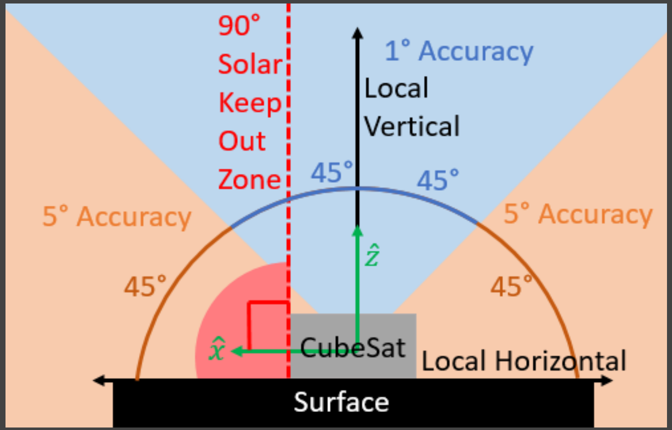
Sun Knowledge

Determine Sun position with 1° accuracy

Sun Knowledge - Full Sky Coverage

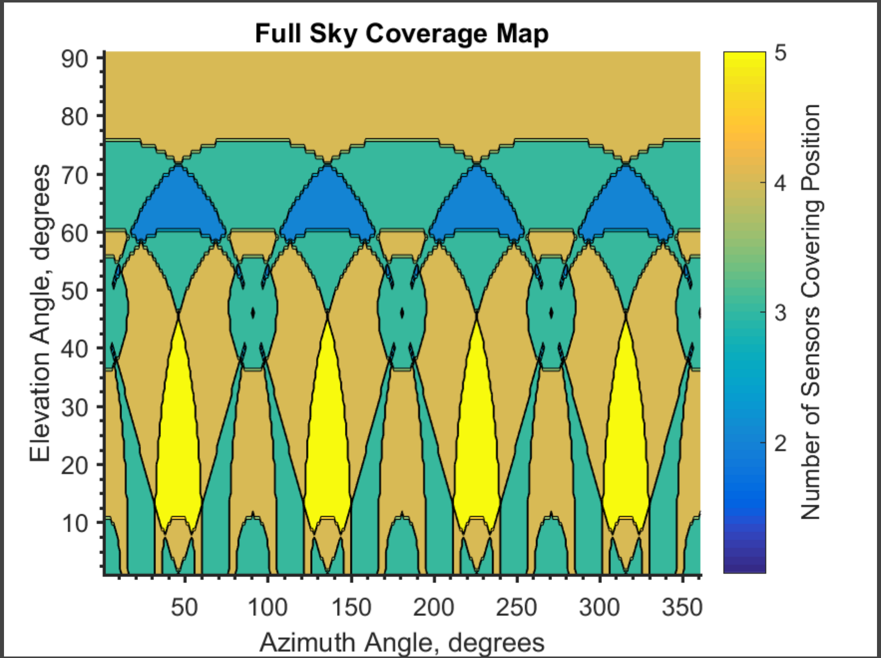
FR 3: The ARS and mechanisms shall open the instrument door that is pointing away from the sun.
3.2.2: The ARS shall determine Sun position to within +/- 5° up to 45° above the surface and to within +/- 1° from 45 ° to 90 ° above the surface.

- Full sky coverage is needed to determine sun position and optimal tilting angle
- Minimum of 2 sensors must see each part of the sky
  - Two dimensional accuracy requirement means only two sensors needed
  - Two sensors will generate two Sun positions - only a difference in azimuth, not elevation



Sun Knowledge - Full Sky Coverage

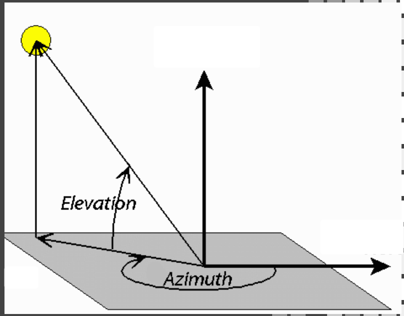
Plot below shows the number of sensors that can see each part of the sky for all azimuth and elevation angles.



Baseline design of 12 sensors mounted 45° off sides and on flat faces with 10° to 60° FOV will allow the full sky to be covered

Minimum of 2 sensors over full sky

Feasible

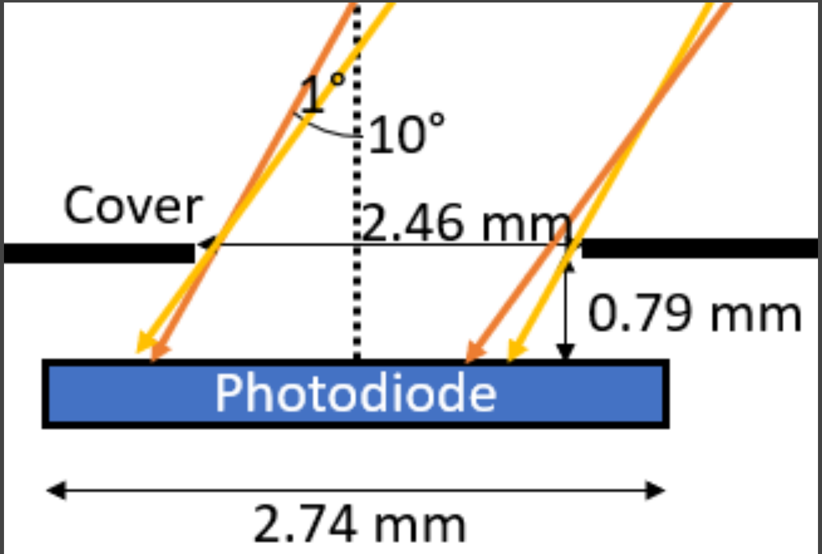


Sun Knowledge - Accuracy

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

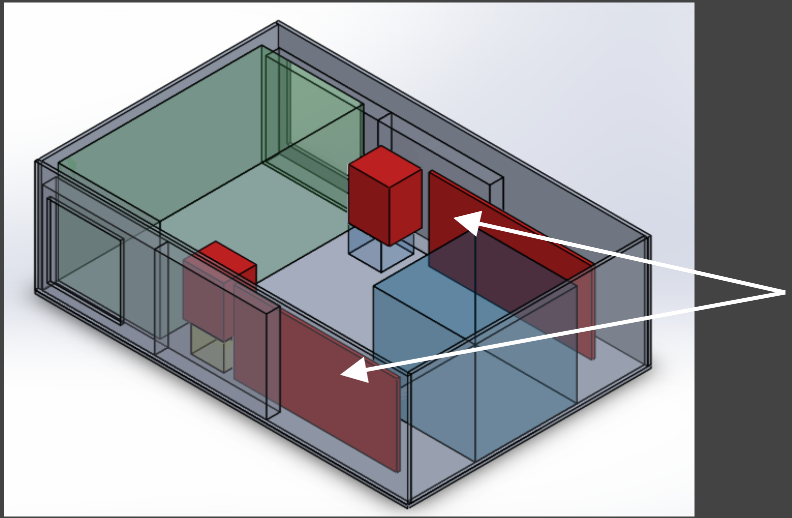
- Calculate input power from solar spectrum
- Calculate current from photodiode gain curve
- Use transimpedance amplifier to create a measureable voltage

ΔVoltage for 10° to 11°
= **160 mV > 0.6 mV**



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

Teensy minimum voltage resolution is 0.6 mV → **Feasible**

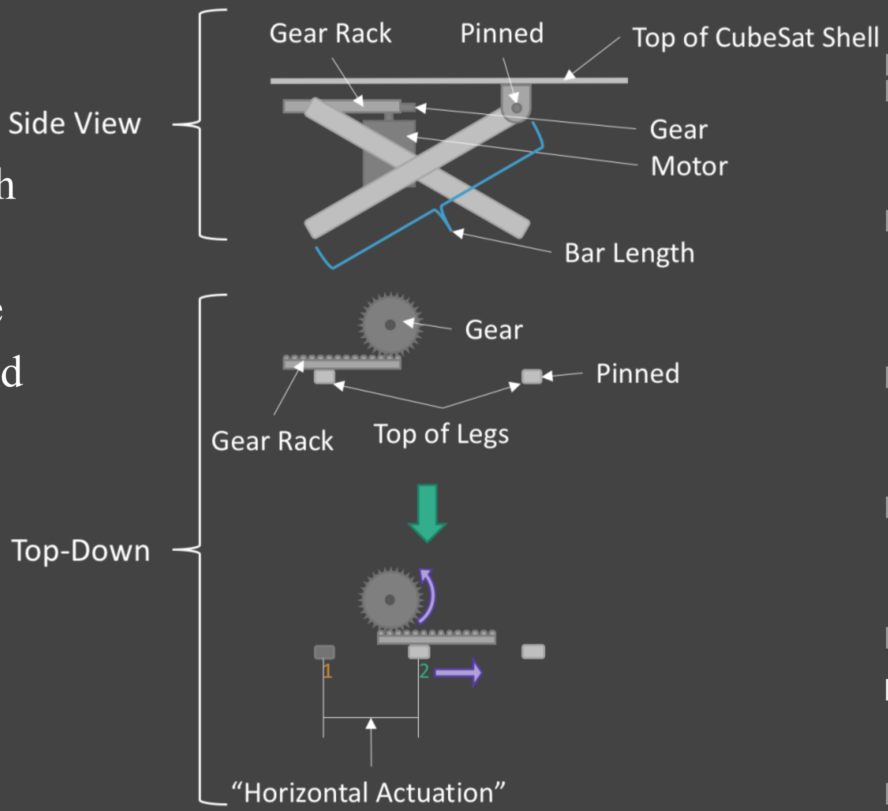


Mechanisms

Tilt in 1° increments up to 45°

Scissor Lift

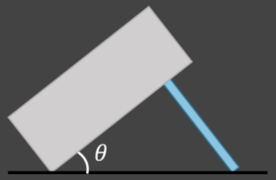
- Lift works by pinning one end and pushing the other toward it
- Possible solution: Servo motor with gear and rack
- Horizontal Actuation: The distance the free bar needs to move to extend the lift to the desired position.

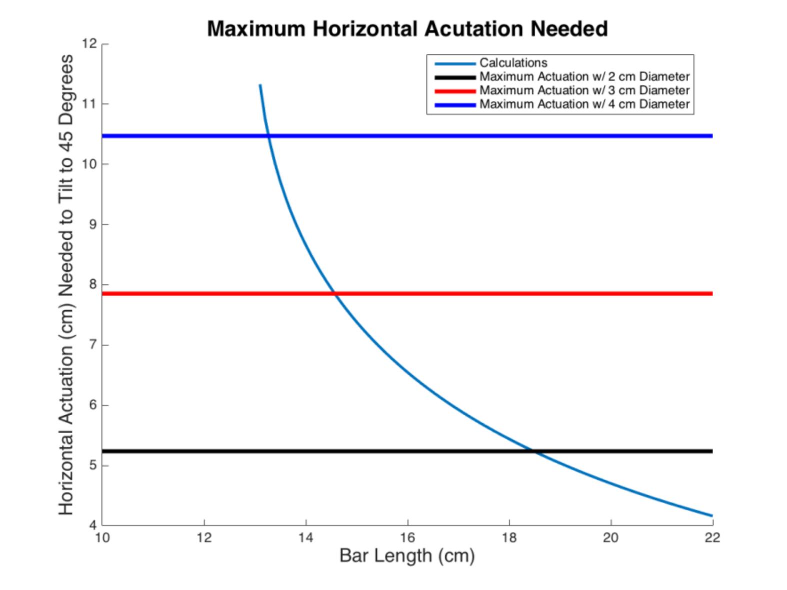


Tilting

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

- Tilt angle is dependent on horizontal actuation
- Maximum turning angle of servo limits horizontal actuation
- Can use different sized gears to increase the amount of actuation





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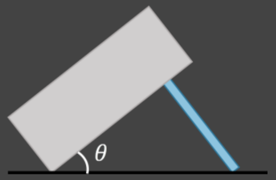

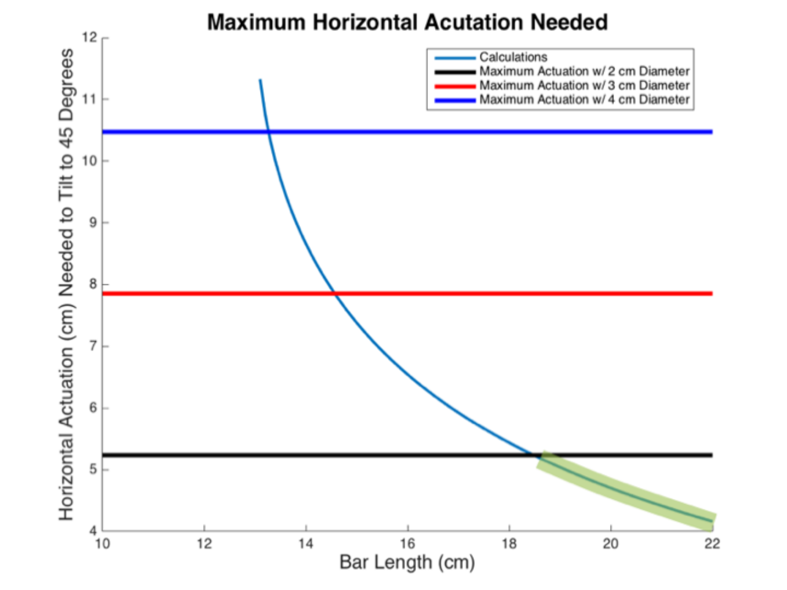

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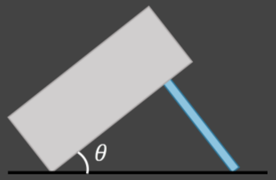

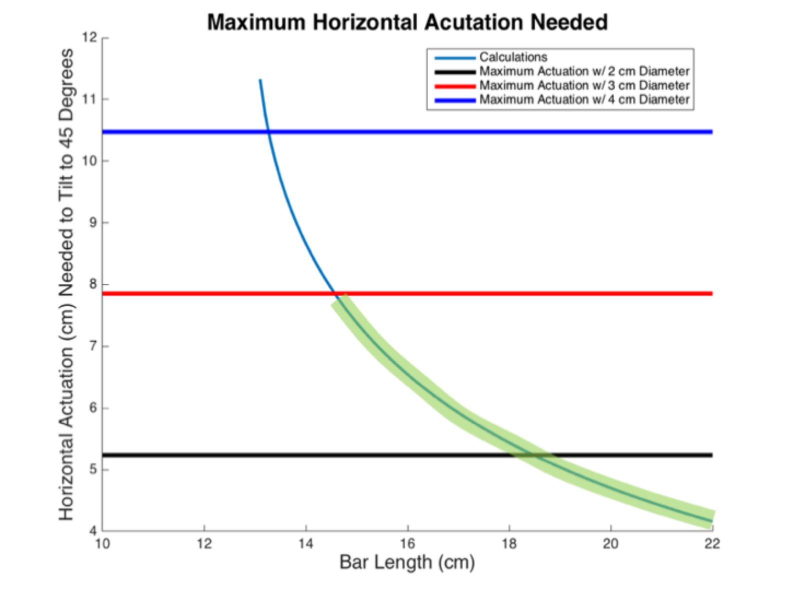

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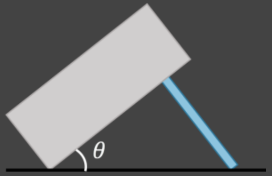
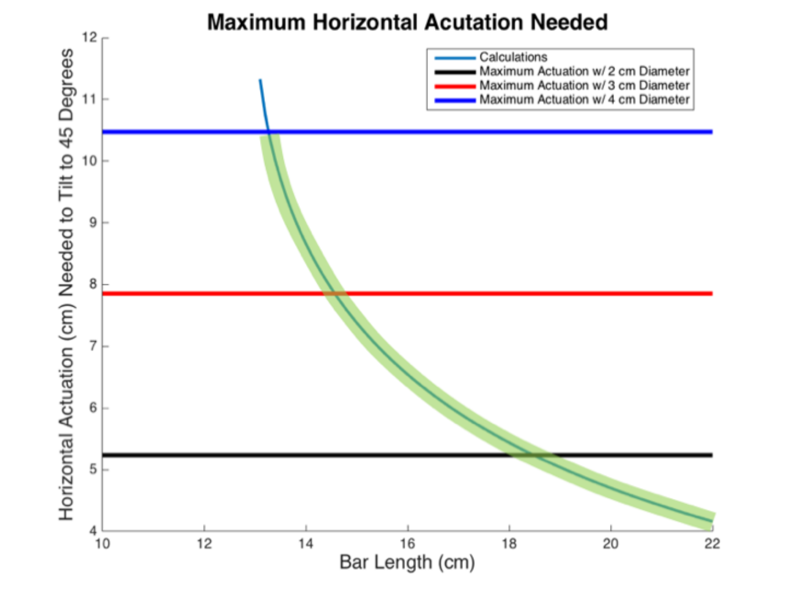


θ= tilt angle

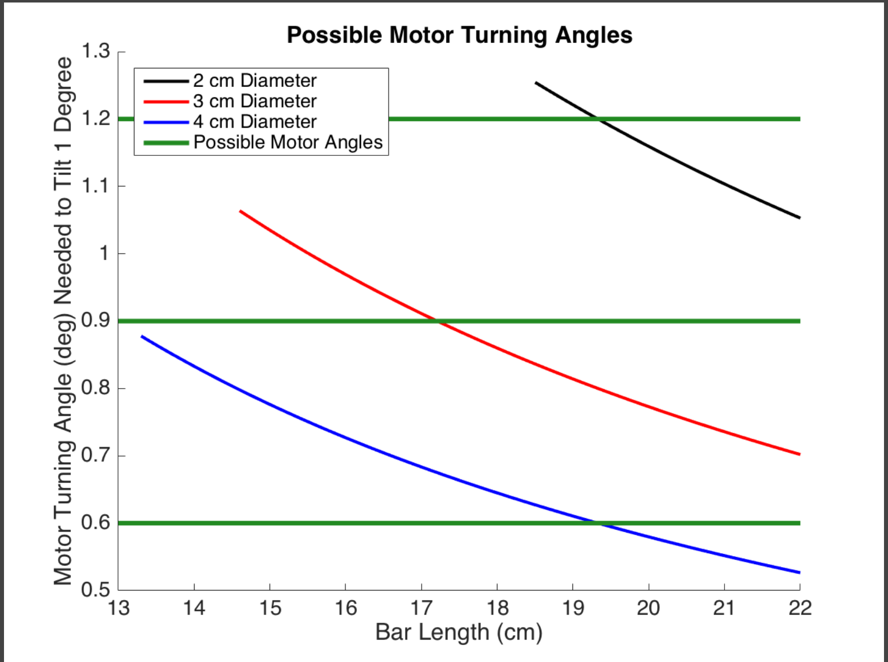


Multiple feasible combinations of gear size and bar length → **Feasible**

Tilting Increment

4.1.2.1. The actuators shall be able to tilt the CubeSat in 1° increments.

- Motor angle required for 1° of tilt is based off of arclength equation
- Servo motors usually have a resolution of ≤ 0.3°
- Cannot meet this requirement if the motor turning angle for 1° of tilt is not a multiple of the resolution



Tilting Increment

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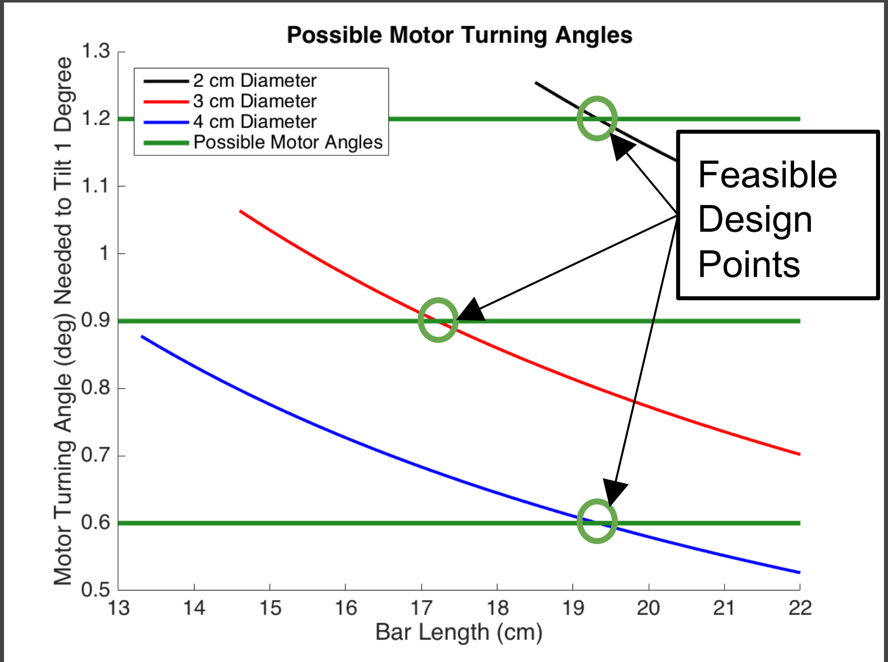
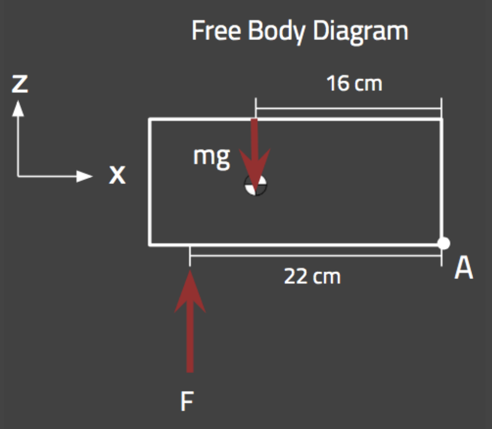


Multiple bar lengths and gear sizes for 1° increments → **Feasible**

Force Required

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

- Center of gravity can vary by +/- 4 cm from the geometric center. Max force required when center of gravity is farthest from the pivot point
- Assume all force from motor is applied straight down



Maximum Force required: 0.71 N

↓

Convert to Torque: 0.16 N m

↓

Motor Torque: 1.5 N m

1.5 N m > 0.16 N m → **Feasible**

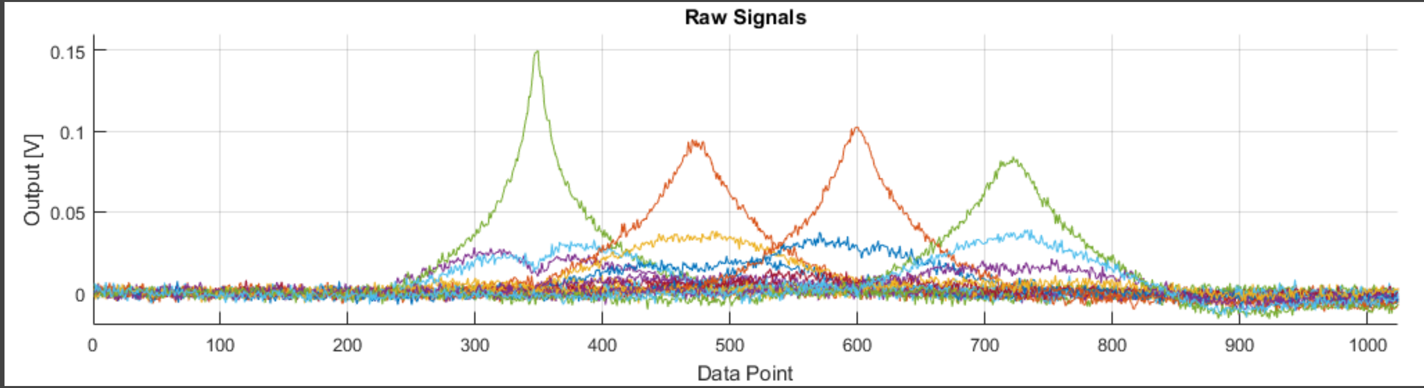
Event Detection

Sample 24 channels @ 1 kHz and run event trigger in real time

Dust Data Example

Instrument data will appear similar to this existing dust data - providing the basis for preliminary testing of event trigger

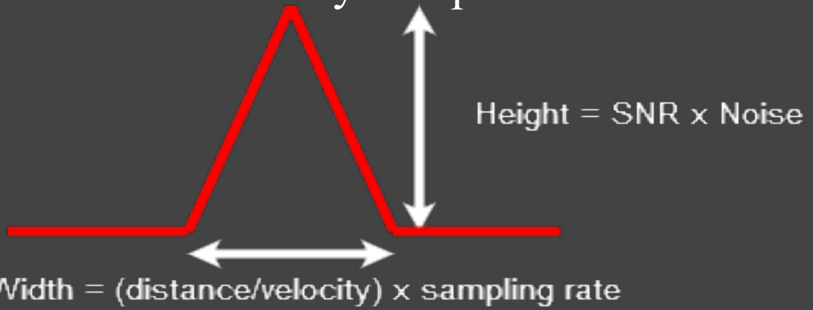
- Each line is the signal from one wire electrode
- Peaks in voltage are due to passing dust inducing charge on the wire
  - Larger voltage means the dust particle is closer to the wire
- Horizontal axis represents samples (taken at an unknown frequency)
  - Shifted peaks show delay as dust passes through wire planes



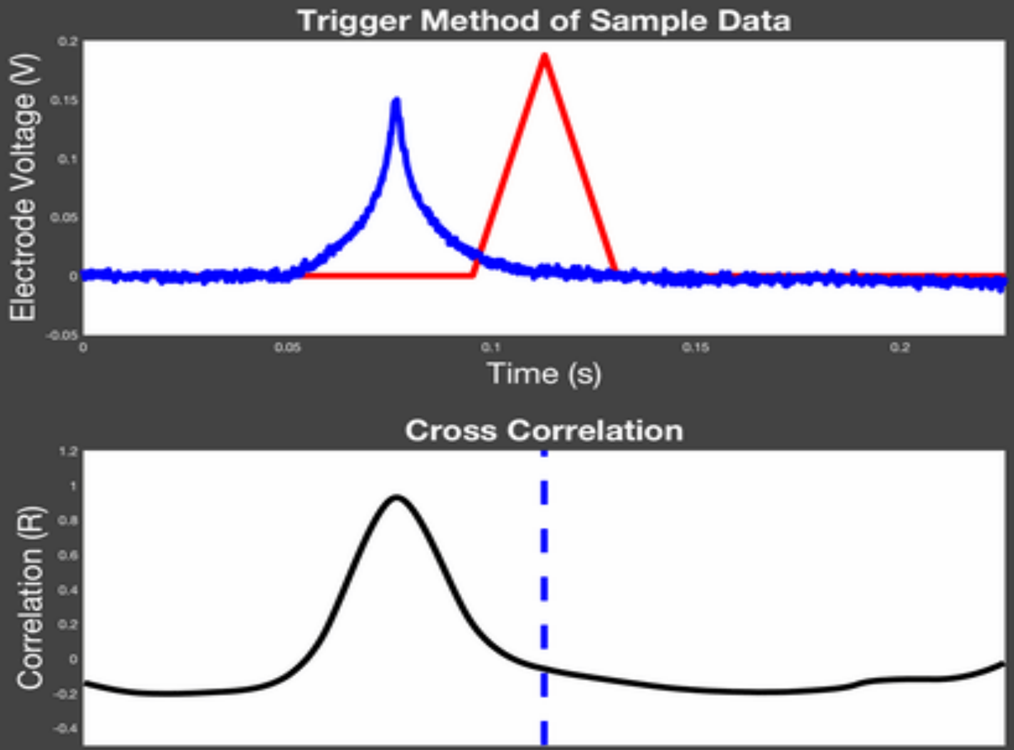
Trigger Method - Filter Creation

6.3.1 The software shall be able to filter environmental noise to determine when an event has occurred

- Large signal data resembles a triangle
  - Height of triangle derived from signal to noise ratio (SNR) 6.25 of previously built charge sensitive amplifier (CSA) circuits
  - Width from estimated velocity of dust particle (1-2 m/s) and processor sampling rate (1 kHz)
- Filter provides a **signal to compare to data** to detect dust events
  - Cross correlation continuously compares filter to incoming dust data

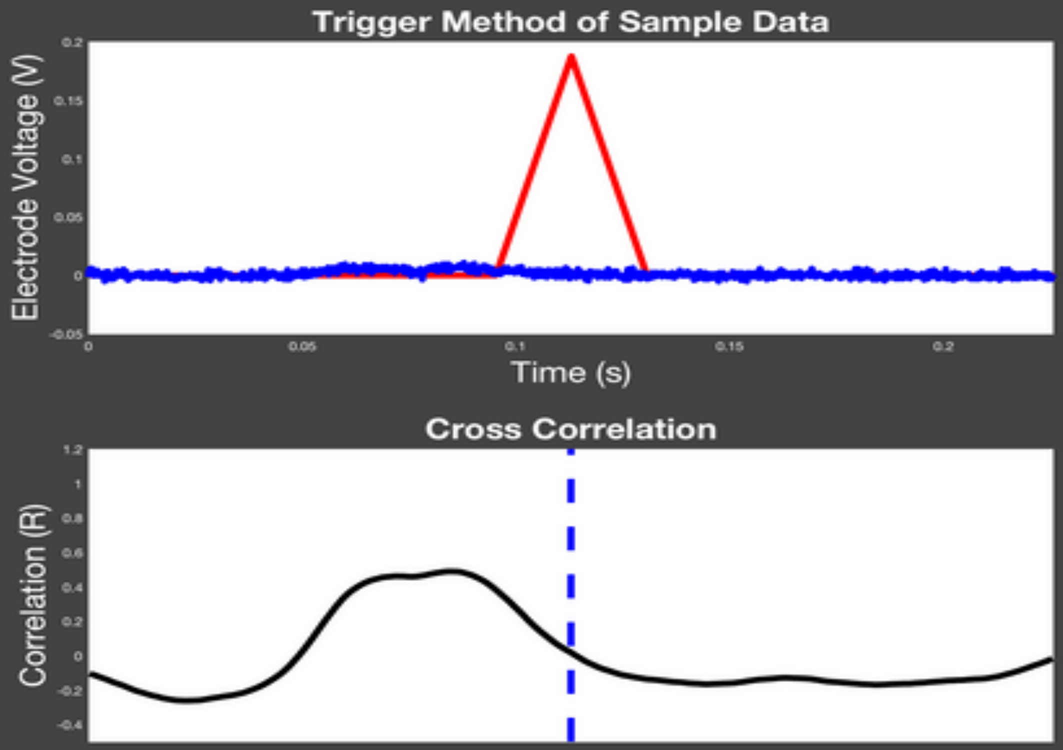


Large Signal Trigger Demonstration



Event is triggered when cross correlation passes the threshold

Small Signal Trigger Demonstration



Successfully triggered with large and small sample signals

Feasible

Electronics: Instrument Microcontroller (MCU)

5.2.1. The hardware shall convert analog signals from each of 24 instrument amplifiers to digital at 1 kHz (total 24 KSPS).
5.2.2. The instrument processor shall be capable of temporarily storing 10 KB of data for a full event to be output if the event trigger software determines an event has occurred.

Representative microcontroller choice:

STMicroelectronics STM32F Series (STM32F427ZI6)

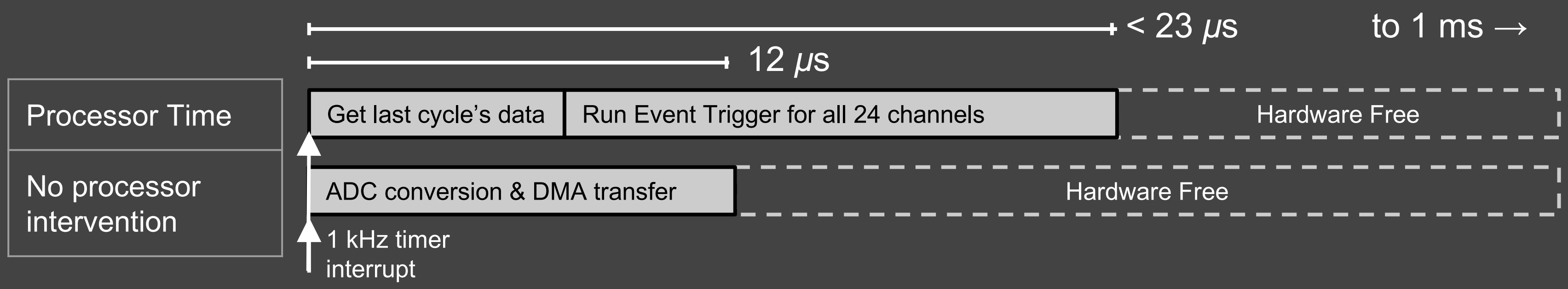
- ARM® Cortex®-M4 core processor (32-bit)
- 180 MHz clock speed
- 256 KB of SRAM
- 24 channels for three 12-bit ADCs (up to 7.2 MSPS)

7.2 MSPS > 24 KSPS
256 KB RAM > 10 KB RAM

Feasible

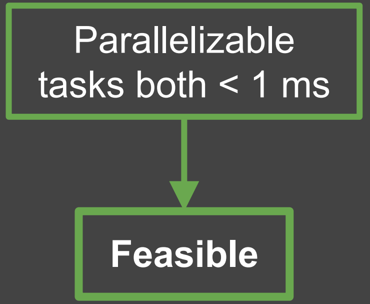
Electronics: Embedded Software Feasibility

5.2. The instrument shall have a processor and ADC array capable of sampling all 24 amplifiers and running the event detection software.



With STM32F427ZI6:

- Worst case ADC conversion: ***12 μs*** for 24 channels
- Estimate event trigger software duration based on algorithm and ARM® Cortex®-M4 instruction set:
  - *< 23 μs*
- Processor free 98% of the time, ADC free 99% of the time



Status Summary and Strategy

Critical Project Elements

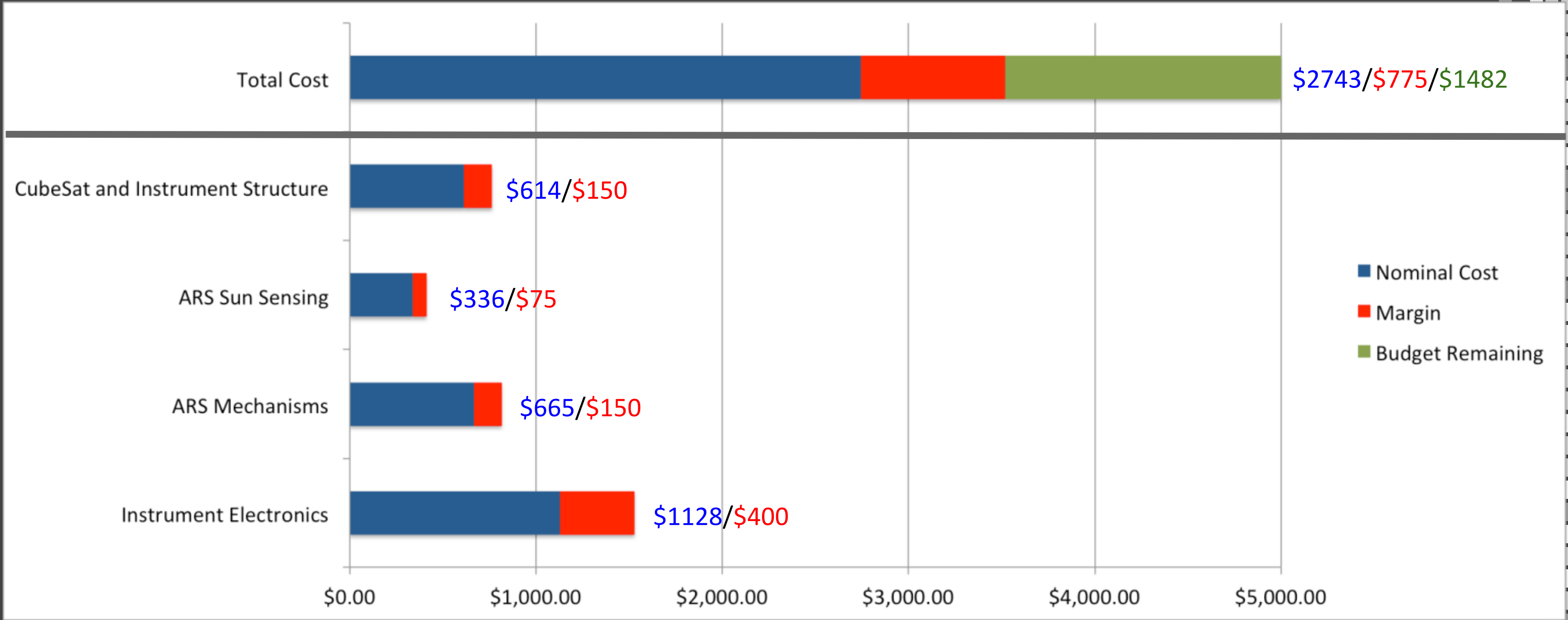
Critical Project Element	Solution
Dust instrument miniaturization	CAD Model Definition
Surviving Impact	Impact Analysis
Sun determination	ARS Sensor Package
Tilting mechanism	ARS Package
Instrument processor and event trigger	Electronics Package

Testing Facilities

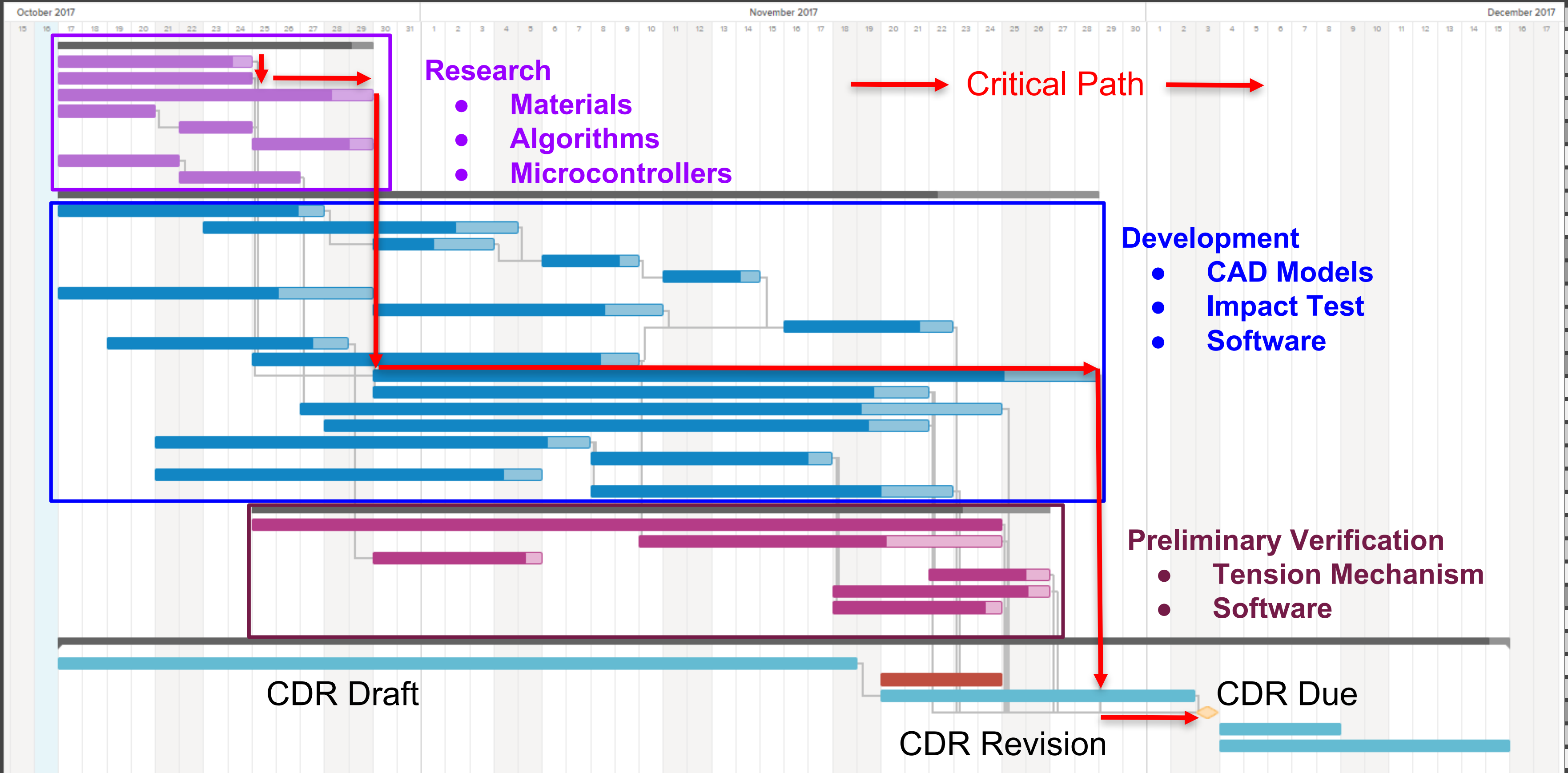
- **Dust Sensing** - IMPACT Lab
- **Impact Testing** - Idea Forge Lansmont 15D Shock Test Machine
- **ARS Mechanisms** - Flat and sandy surface with specific grain size
- **ARS Sensors** - Sommers-Bausch Observatory
  - Provides a known attitude relative to the sun
  - Need to contact SBO to discuss availability

Budget

Feasible



Gantt Chart



October 2017
November 2017
December 2017
Research
● Materials
● Algorithms
● Microcontrollers
Critical Path
Development
● CAD Models
● Impact Test
● Software
Preliminary Verification
● Tension Mechanism
● Software
CDR Draft
CDR Due
CDR Revision

Moving Forward

- **Mechanisms:** design gear rack systems with choice for motor and locking mechanism
- **Sun Sensing:** Correlate photodiode output to solar position, create closed loop control system for tilt actuation.
- **Software:** translate algorithm to embedded software to find cross correlation in real time, output dust events over serial once detected
- **Electronics:** finalize real-time architecture and MCU choice
- **Impact modeling:** SOLIDWORKS Drop Test simulation, explore wire failure modes, refine impact time

Acknowledgements

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- Matt Rhode
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- Dr. Torin Clark
- Jenny Kampmeier
- Lee Huynh
- Tim Kiley

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[11]"Silicon PIN Photodiode" http://www.vishay.com/docs/84679/temd501.pdf

Thank you!

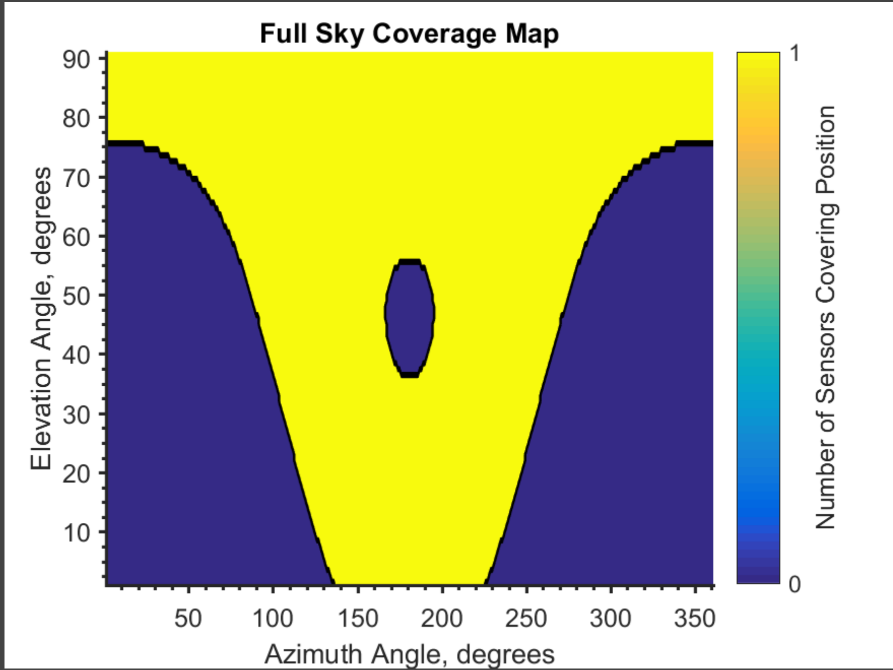
Feedback?

Backup Slides

Slide Directory

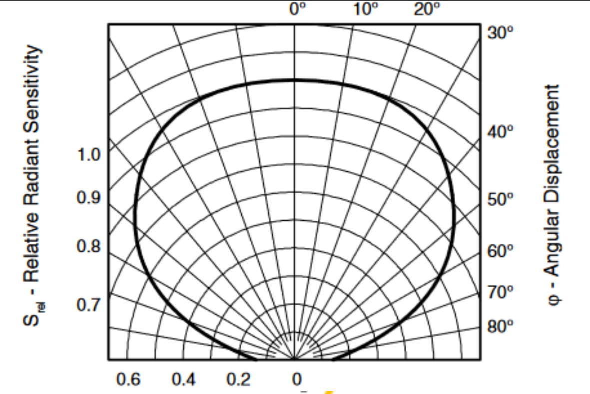
Sun Knowledge - Accuracy

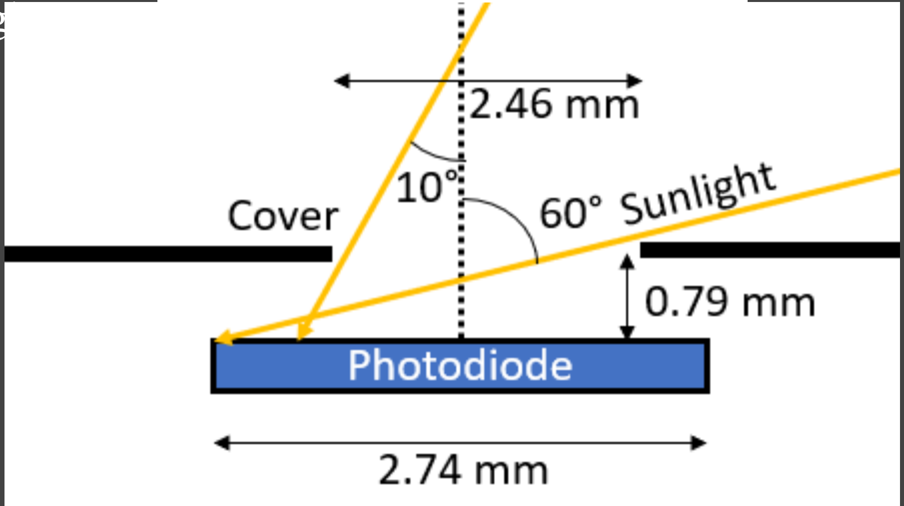
- One Photodiode can cover a ‘doughnut’ shaped piece of sky
- Cover restricts incoming sunlight, but prevents sensing near the photodiode boresight
  - Maximum angle off center: 60°
  - Minimum angle off center: 10°



Sun Knowledge - Accuracy

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

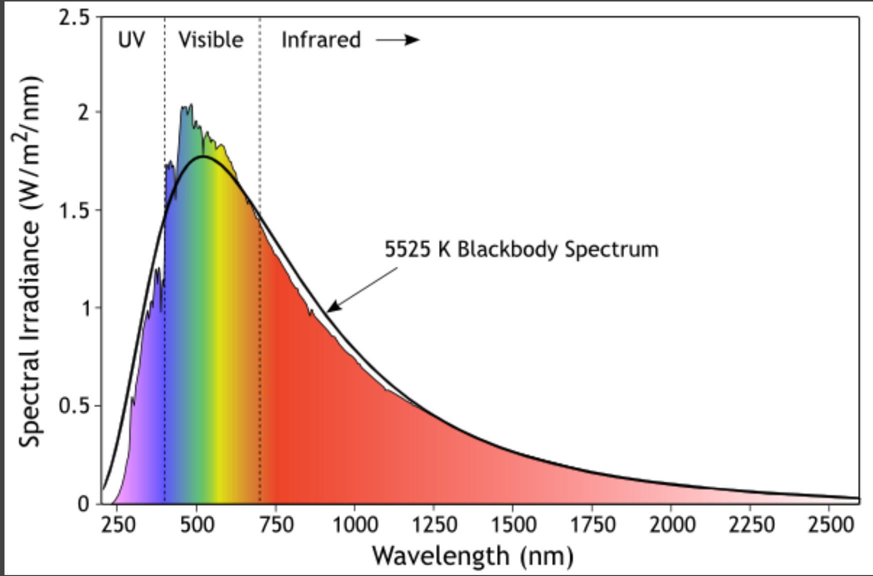




Sun Knowledge - Accuracy

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



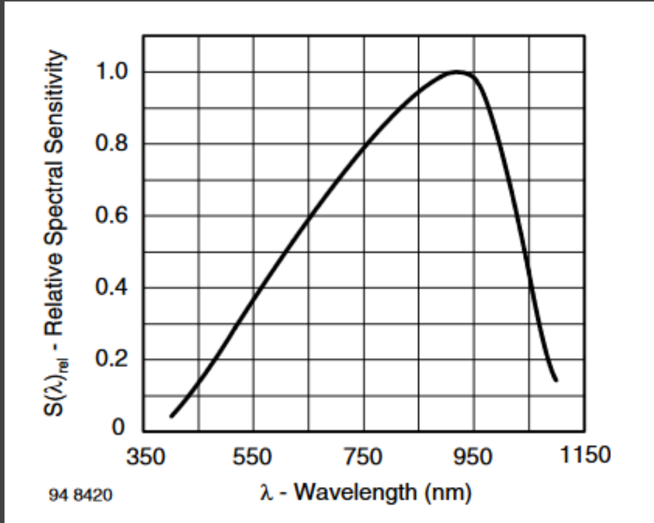
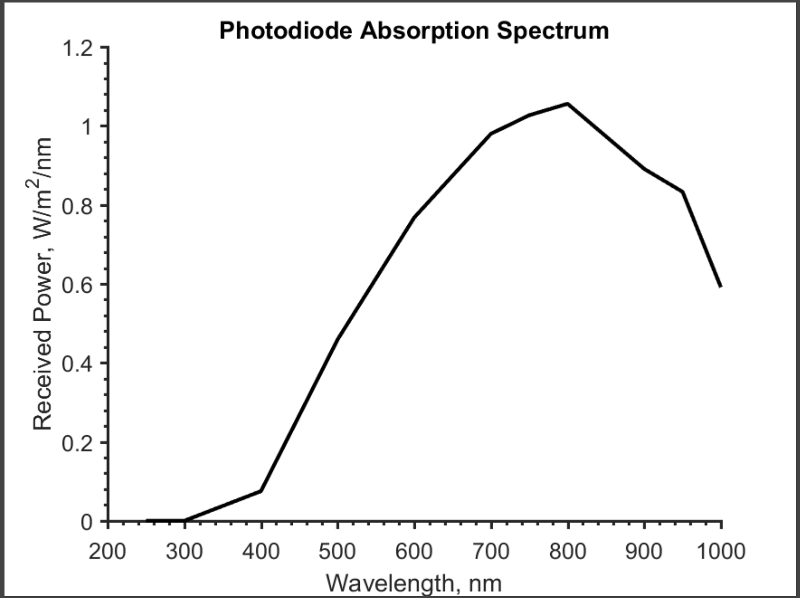


Fig. 6 - Relative Spectral Sensitivity vs. Wavelength

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.

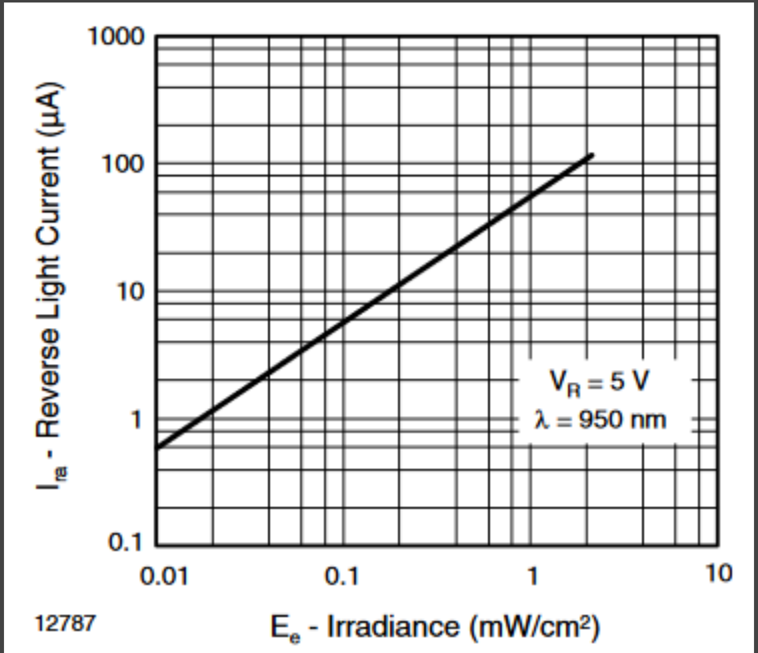
Ir = 457.5 W/m^2

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**

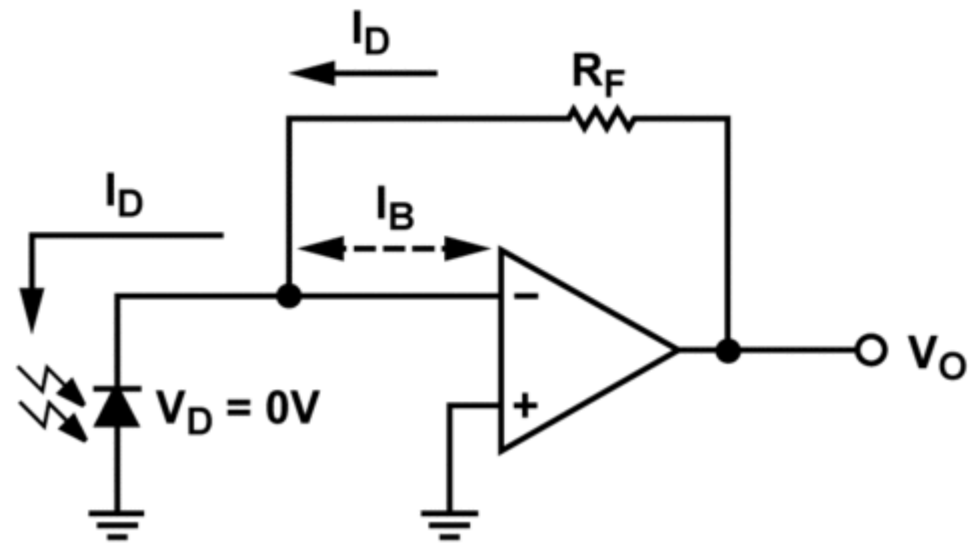


Sun Knowledge - Accuracy

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**



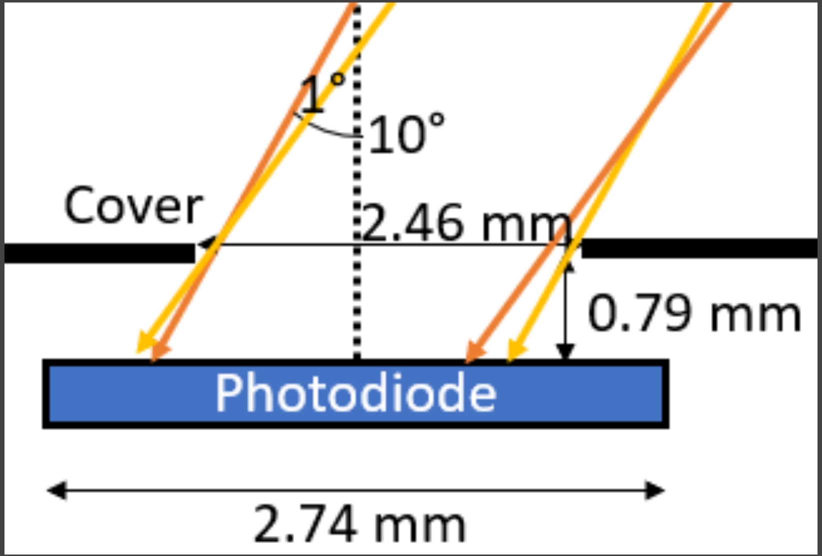
Sun Knowledge - Accuracy

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

10° power = 3.43 mW
11° power = 3.41 mW

10° current = 30 μA
11° current = 29 μA

10° Voltage = 4.80 V
11° Voltage = 4.64 V



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

Teensy minimum voltage resolution is 0.0006 V → **Feasible**

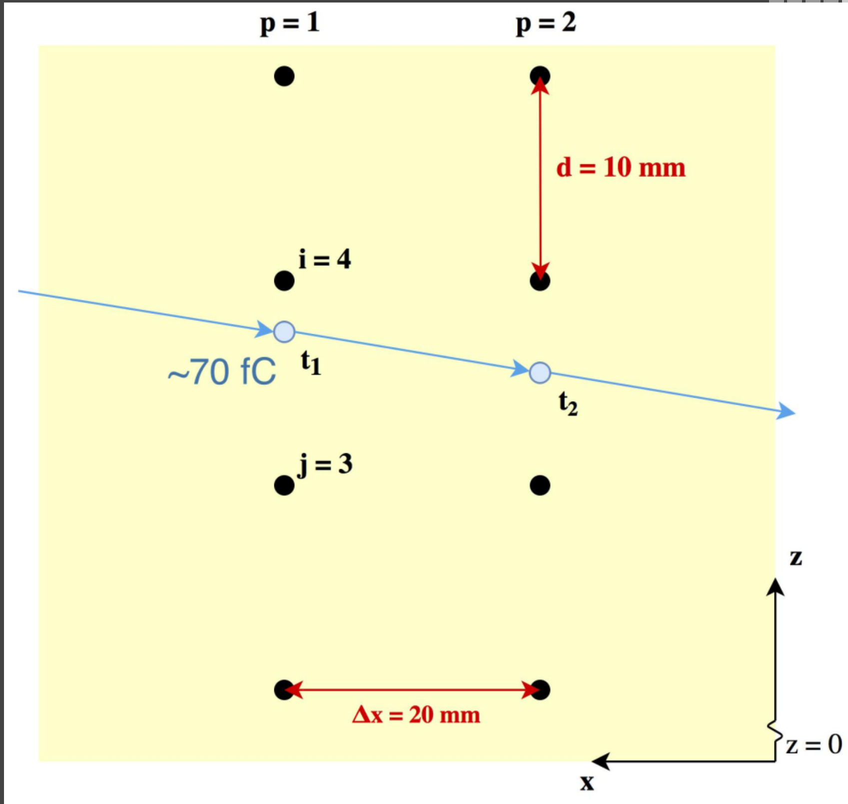
Instrument

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

Methods for Q, v, & m extraction

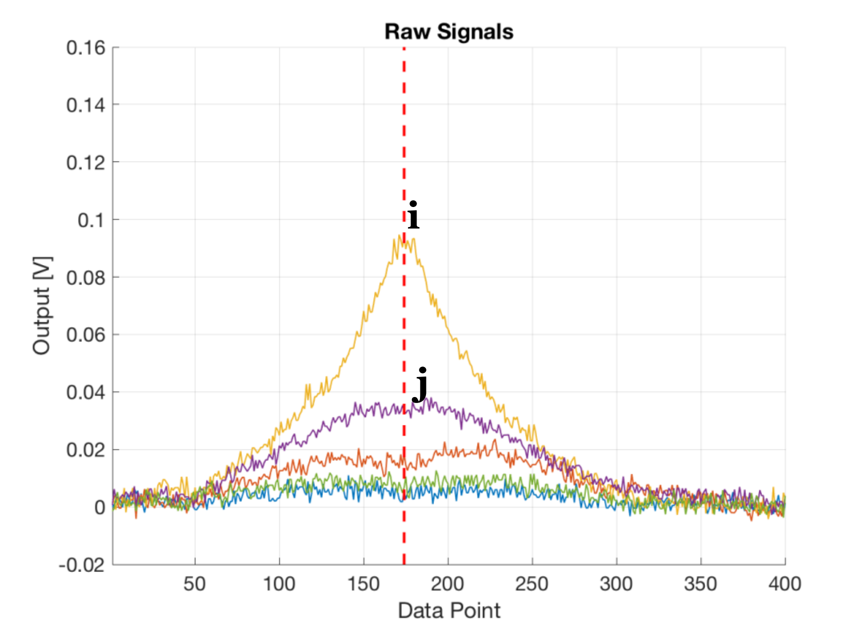
- Definitions:
  - p ~ plane number
  - n ~ wire number in given plane
  - i ~ wire w/ highest voltage
  - j ~ wire w/ 2nd highest voltage
  - t_p ~ time particle crosses plane p
  - d ~ wire spacing
  - Δx ~ plane spacing
  - h_n ~ z-coordinate of wire n
  - q_n ~ charge induced on wire n

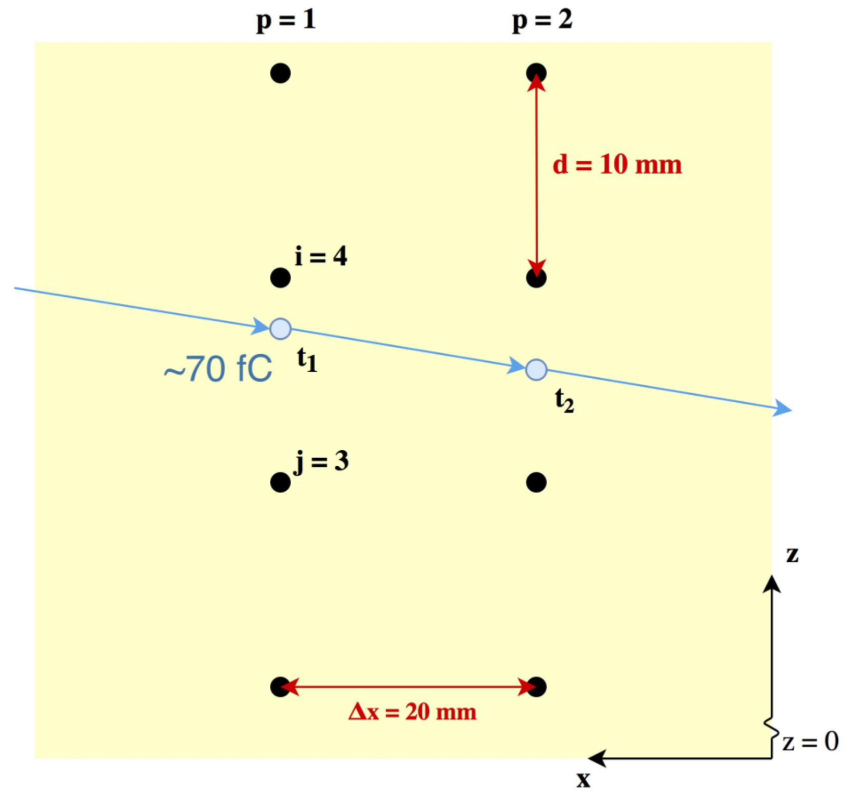
DTS Unit (sub-section)



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

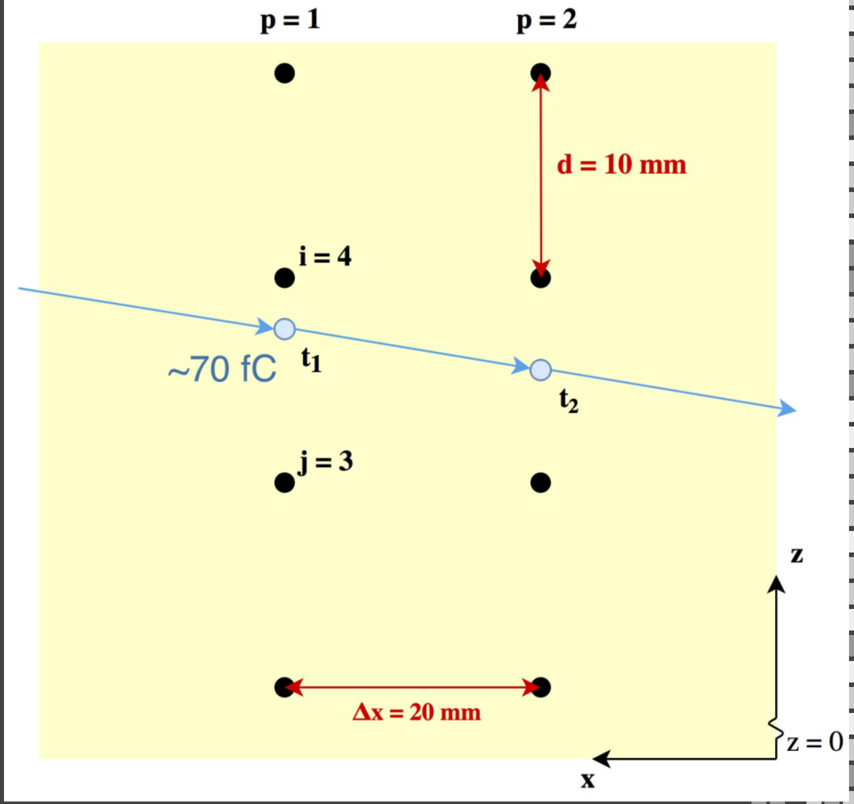
Steps:

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

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

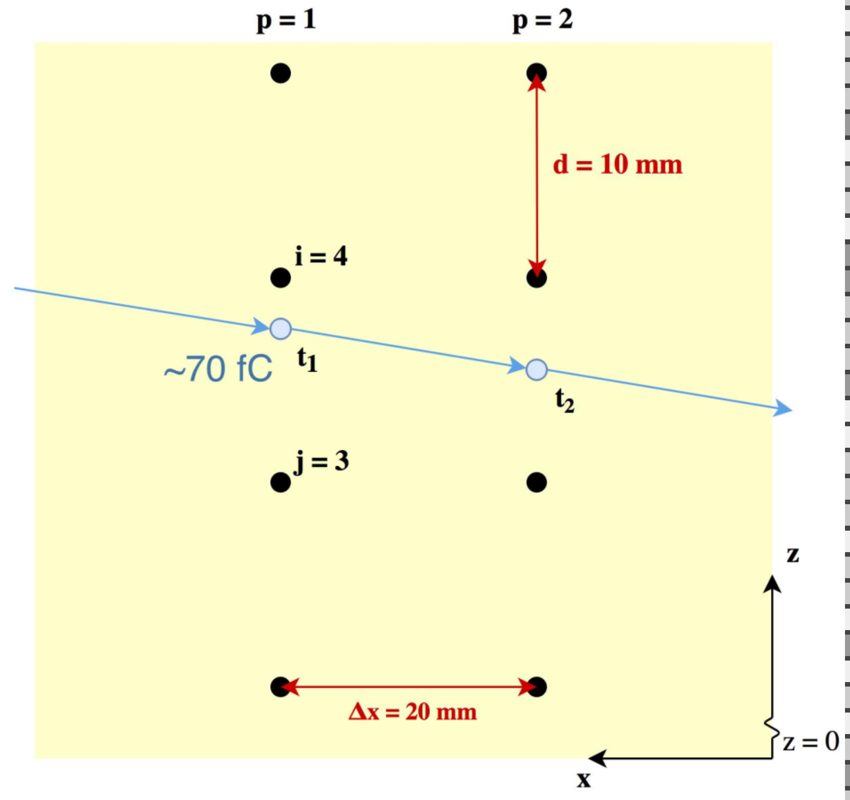
2. Absolute z-coordinate

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

$(p = 1 \rightarrow 4)$

DTS Unit (sub-section)



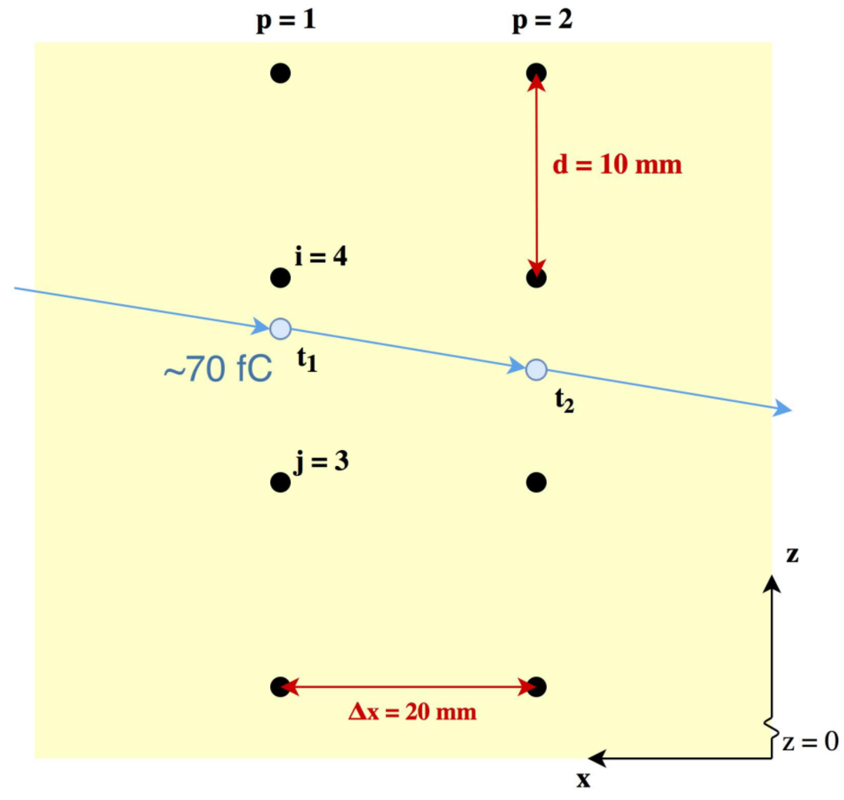
Methods for Q, v, & m extraction

Steps (Cont.):

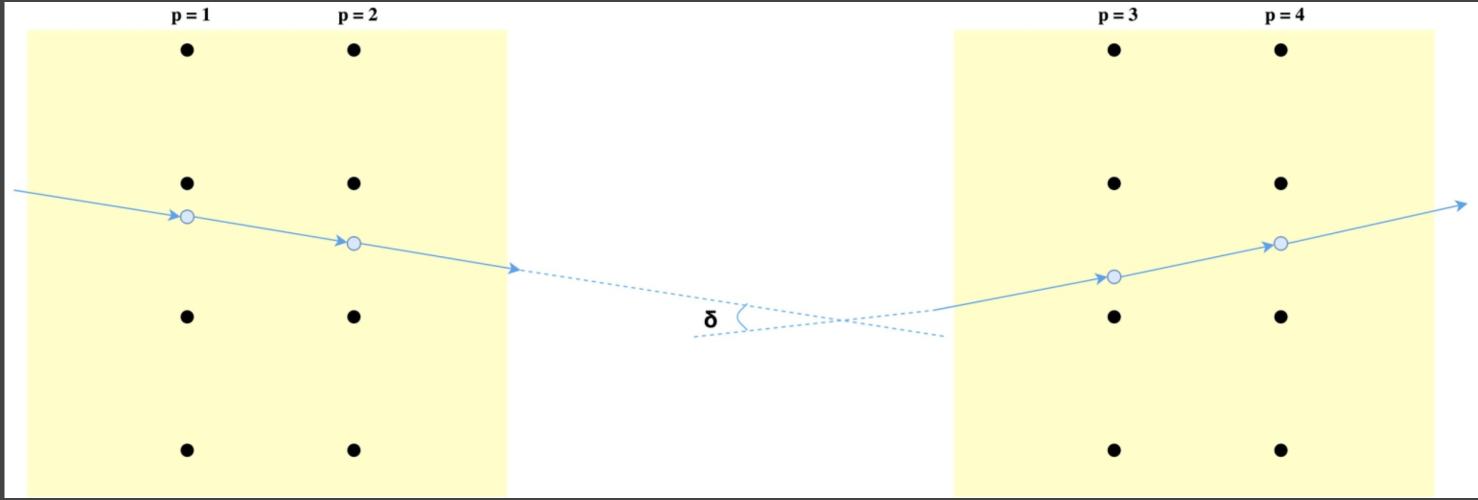
5. Velocity calculation

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

DTS Unit (sub-section)



Methods for Q, v, & m extraction

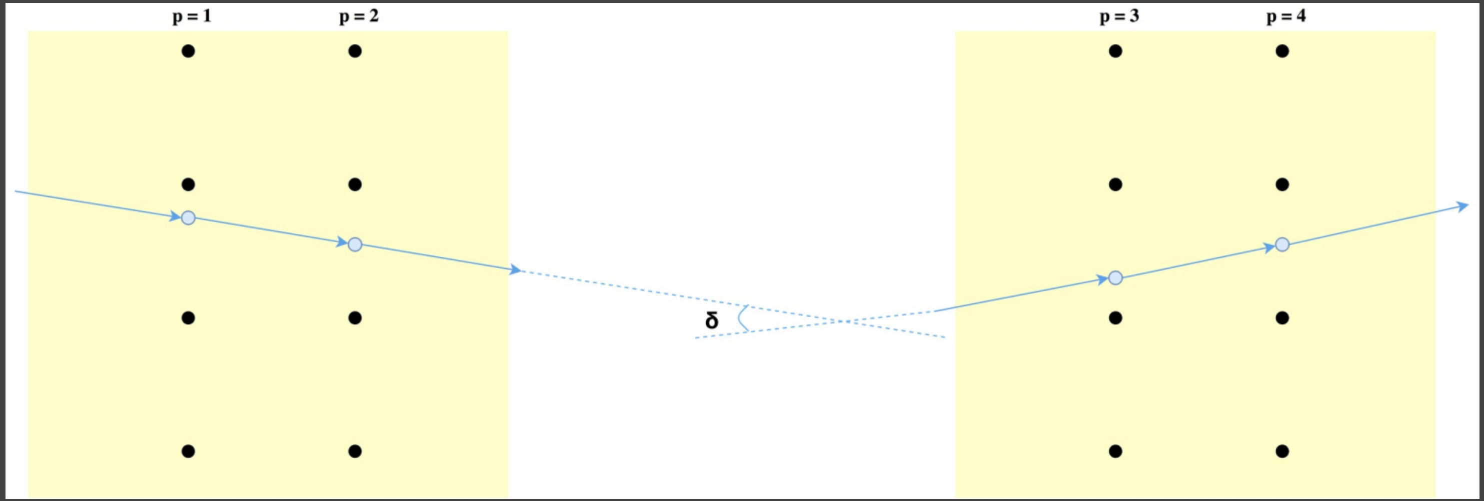


Steps (Cont.):

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.):

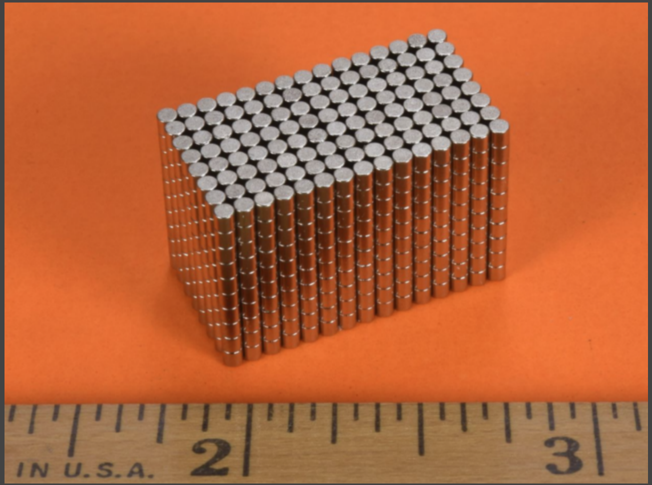
7. Calculate mass (where l = 0.07 m is the length of the deflection region)

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

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

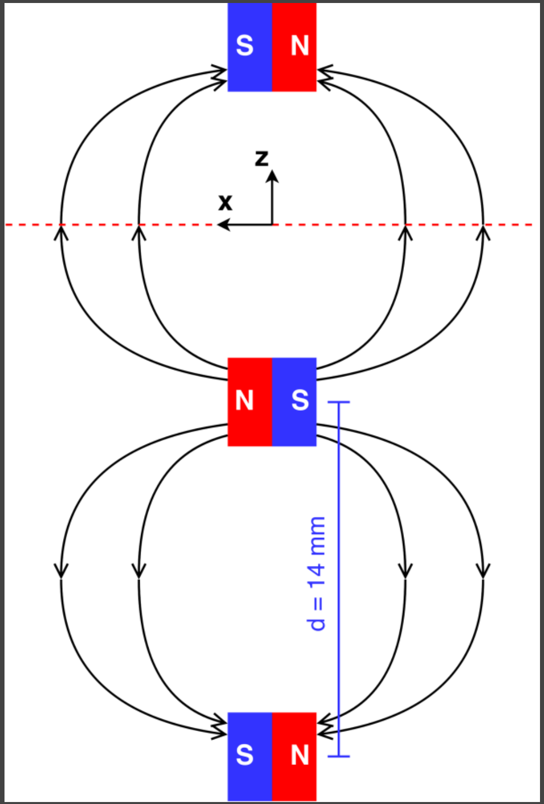


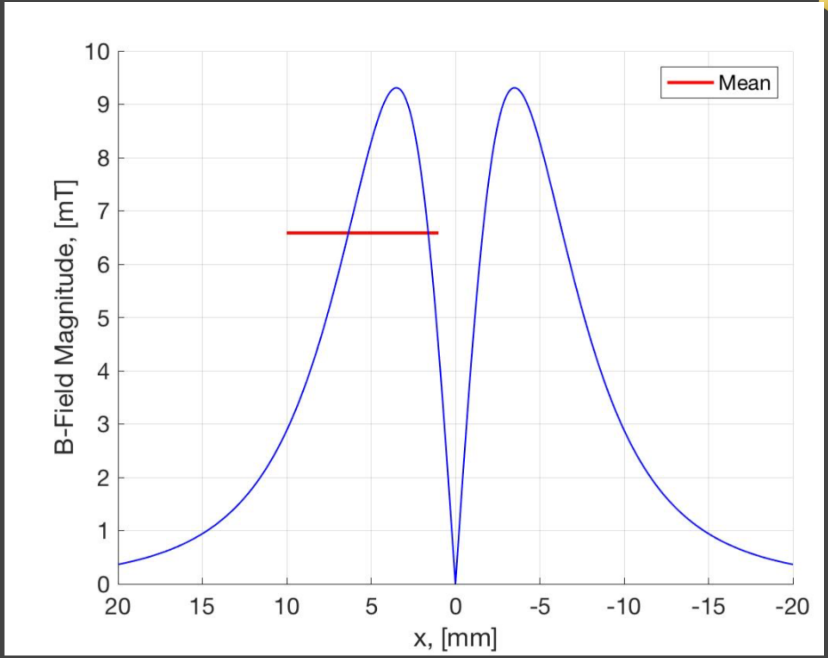
- Need to prove gyroradius of 100 eV electron to be sufficiently as to not penetrate the instrument more than 1 cm (first wire plane)
- Gyroradius:

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

Electron Deflection

Using six magnet bars: d = 14 mm

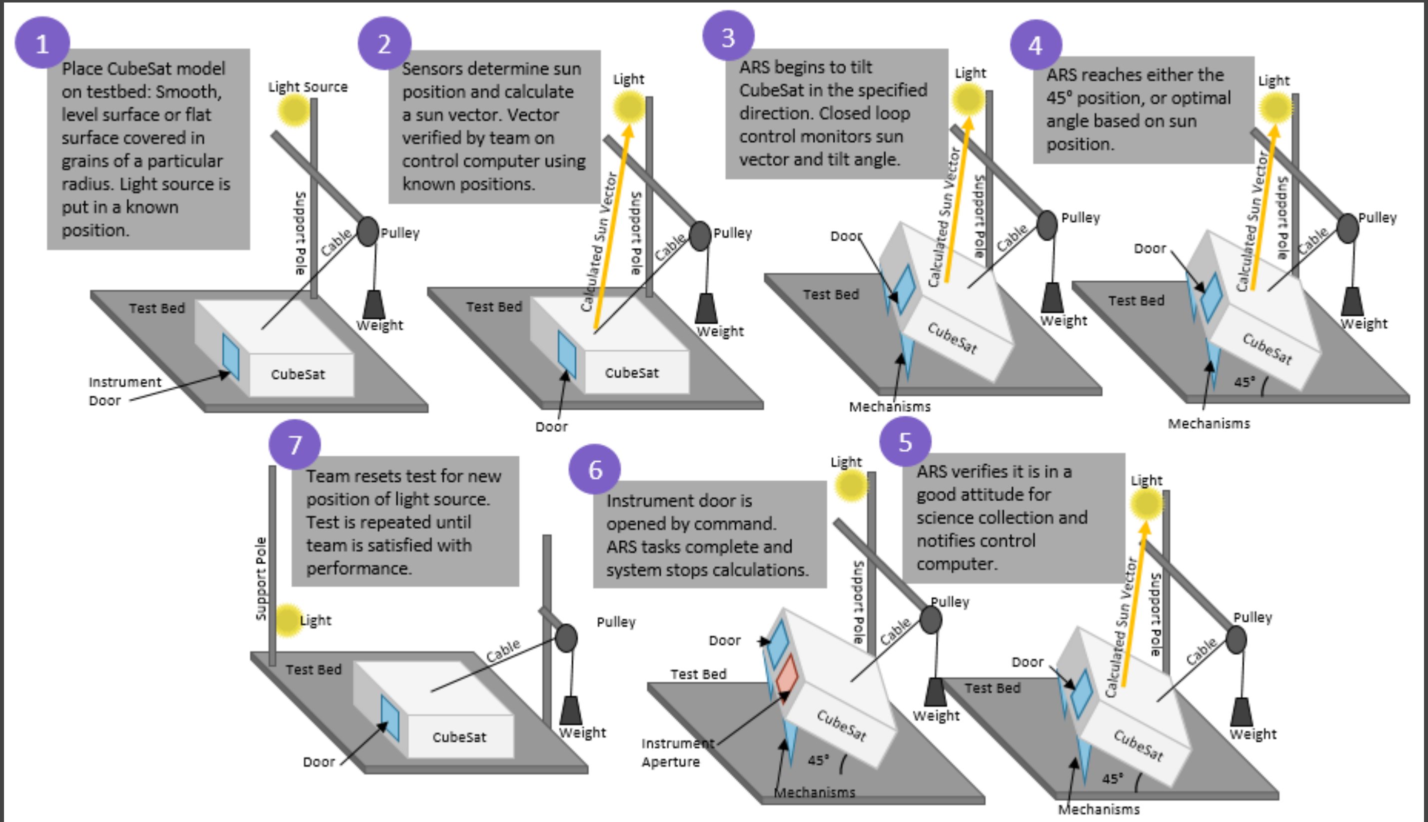




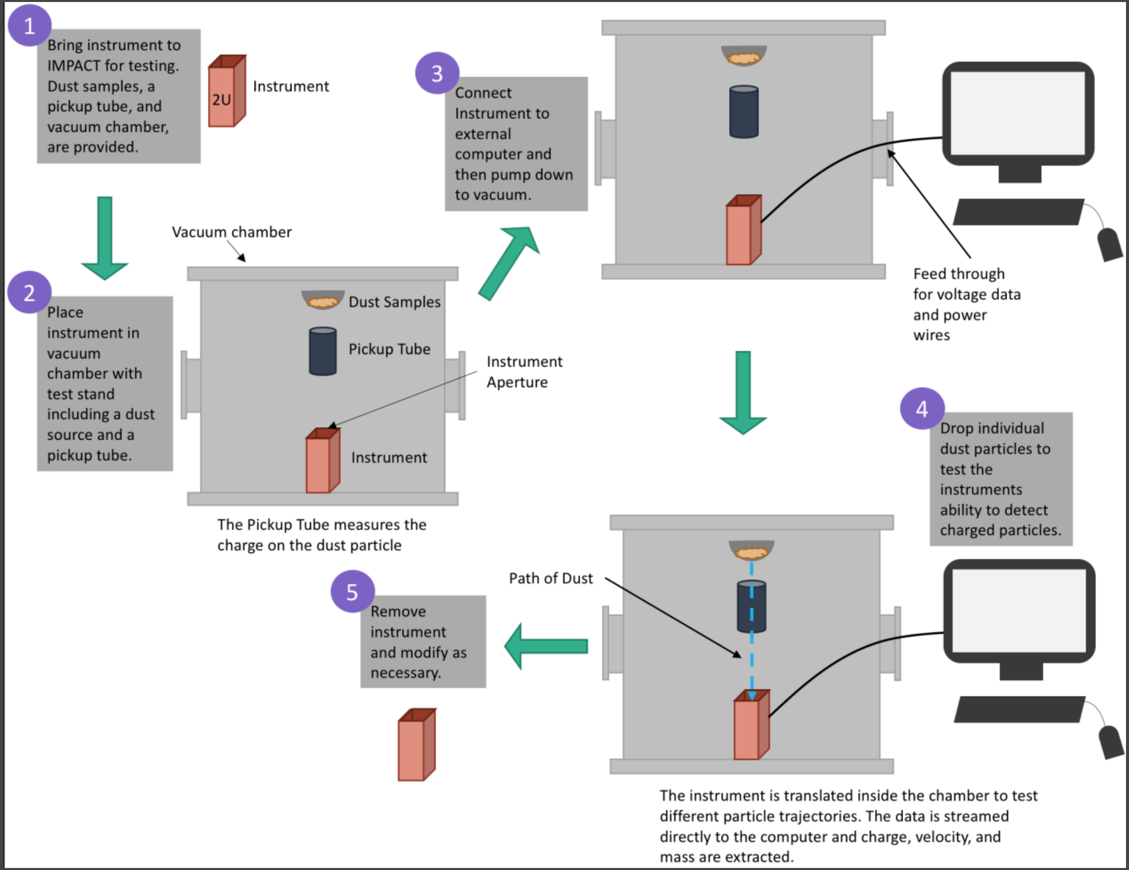
From 10 → 1 mm: $B_{mean} \approx 6.6$ mT

$r_q \approx 5.1$ mm (e^- gyroradius)

ARS Test ConOps

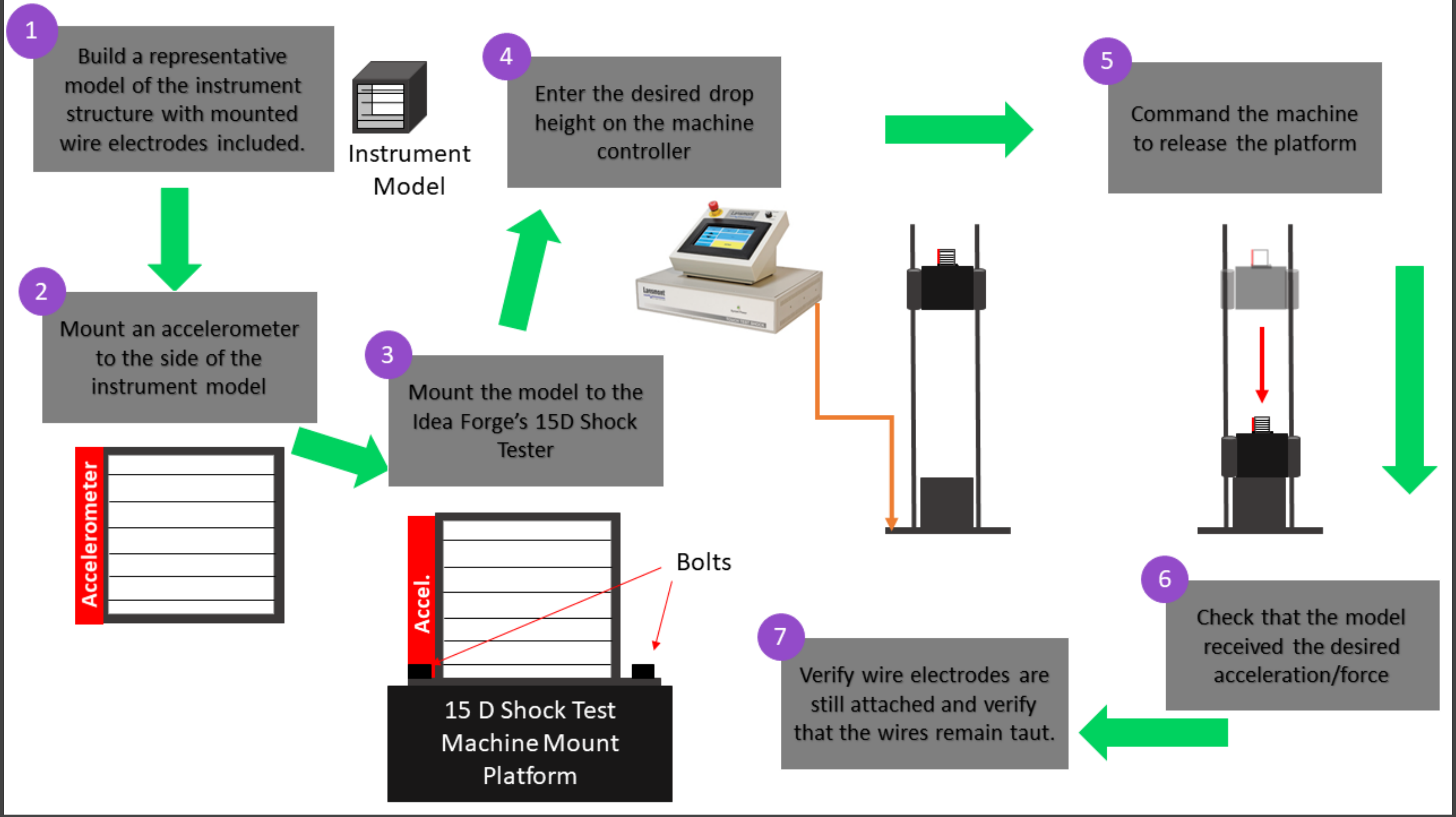


Instrument Test ConOps



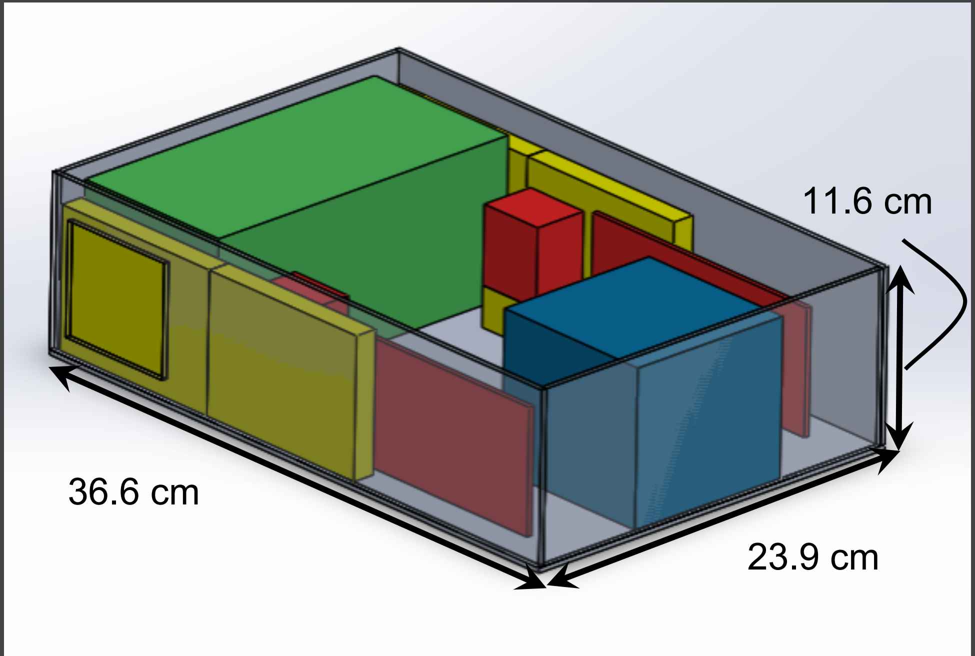
Structures Backup Slides

Impact Test ConOps

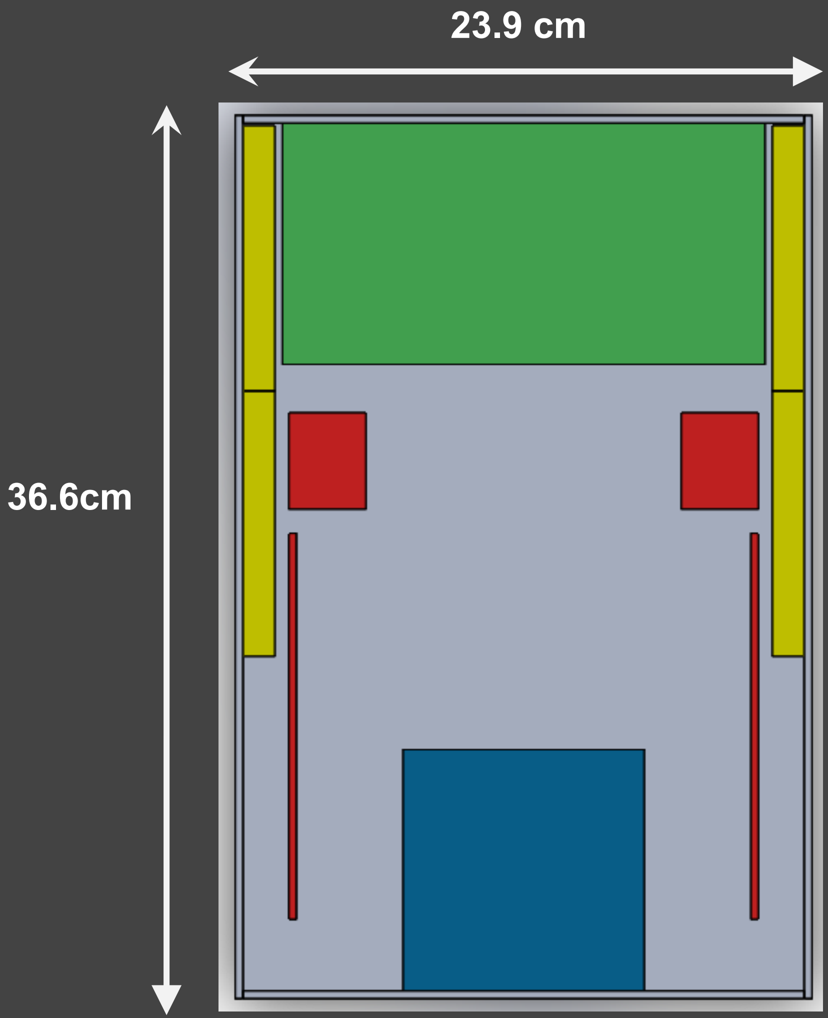


6U CubeSat Model

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



All major subsystems contained in 6U CubeSat Model → **Feasible**



Top View of CubeSat Model

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

6U CubeSat Model

1.1: The CubeSat model -- containing all project subsystems -- and instrument combined shall have a maximum total mass of 12 kg.

System	Mass
Dust Instrument	0.7355 kg
Door Mechanism	0.3580 kg
Scissor Lift Mechanism	0.6600 kg
Avionics (Out of Scope)	1.5000 kg
Microcontrollers (not pictured)	0.1000 kg
CubeSat Model Shell	2.5000 kg
Total Mass	5.8535 kg

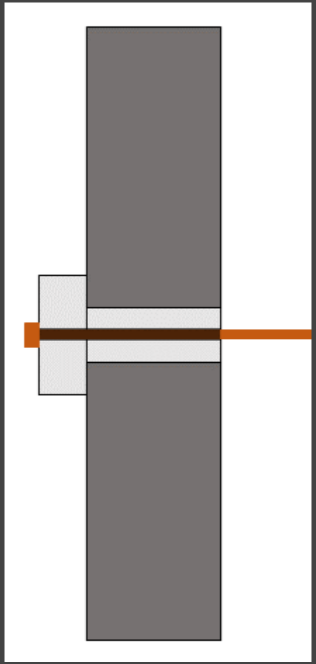
Total Mass < Mass Requirement
5.8535 kg < 12.0000 kg

Feasible

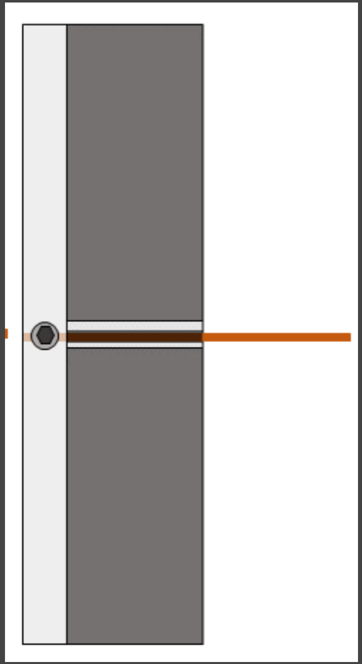
Tension Mechanism Trade Study Metrics

Manufacturability: ability to manufacture the design
Tension Control: precision and control over tension in wires
Volume: there is a limited amount of volume available to fit in the 2U volume
Impact Risk: what type of failure could occur from impact and the risk associated with it

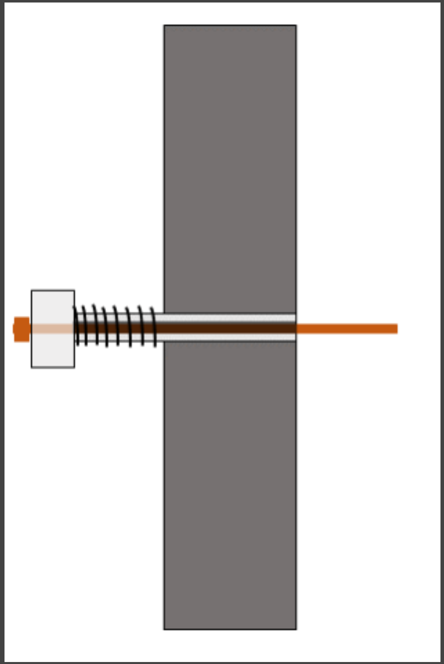
Tension Mechanism Trade Study Options



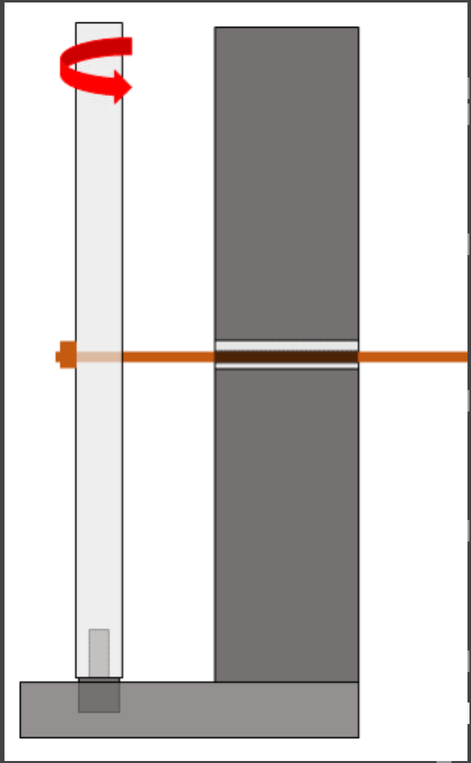
Bolt



Winch



Plate



Post

Trade Study Table

	Weight	**Bolt**	**Winch**	**Plate**	**Post**
Manufacturability	0.3	5	4	5	4
Tension Control	0.35	5	5	5	4
Volume Needed	0.10	3	2	2	3
Impact Risk	0.25	4	3	4	2
Weighted Score		**4.55**	3.9	4.45	3.4

Impact Collision Calculations

Assumptions:

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

Knowns:

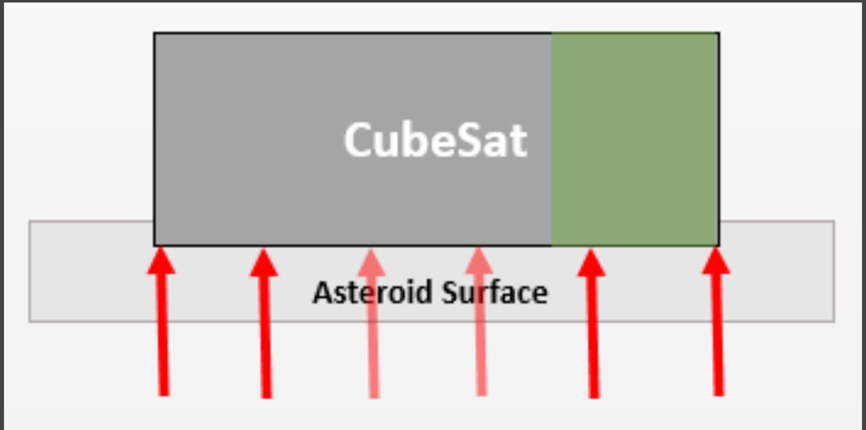
- CubeSat mass (m_{CS}) = 12 kg (max)
- Impact velocity (v_i) = 10 m/s

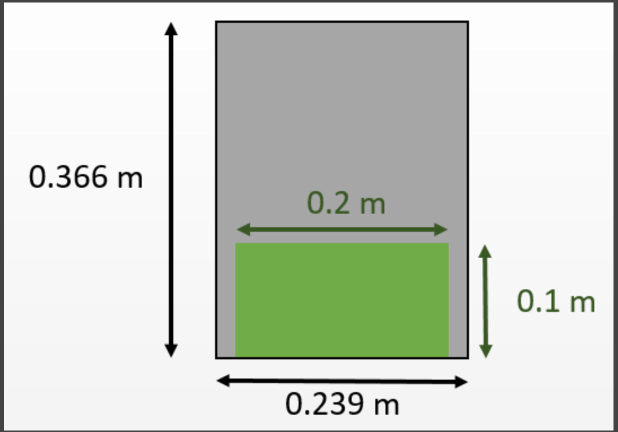
$$J_{CS} = m_{CS}(v_f - v_i)_{CS} = 12(10 - 0) = 120Ns$$

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

Impact Collision Calculations

Point mass force will likely be distributed

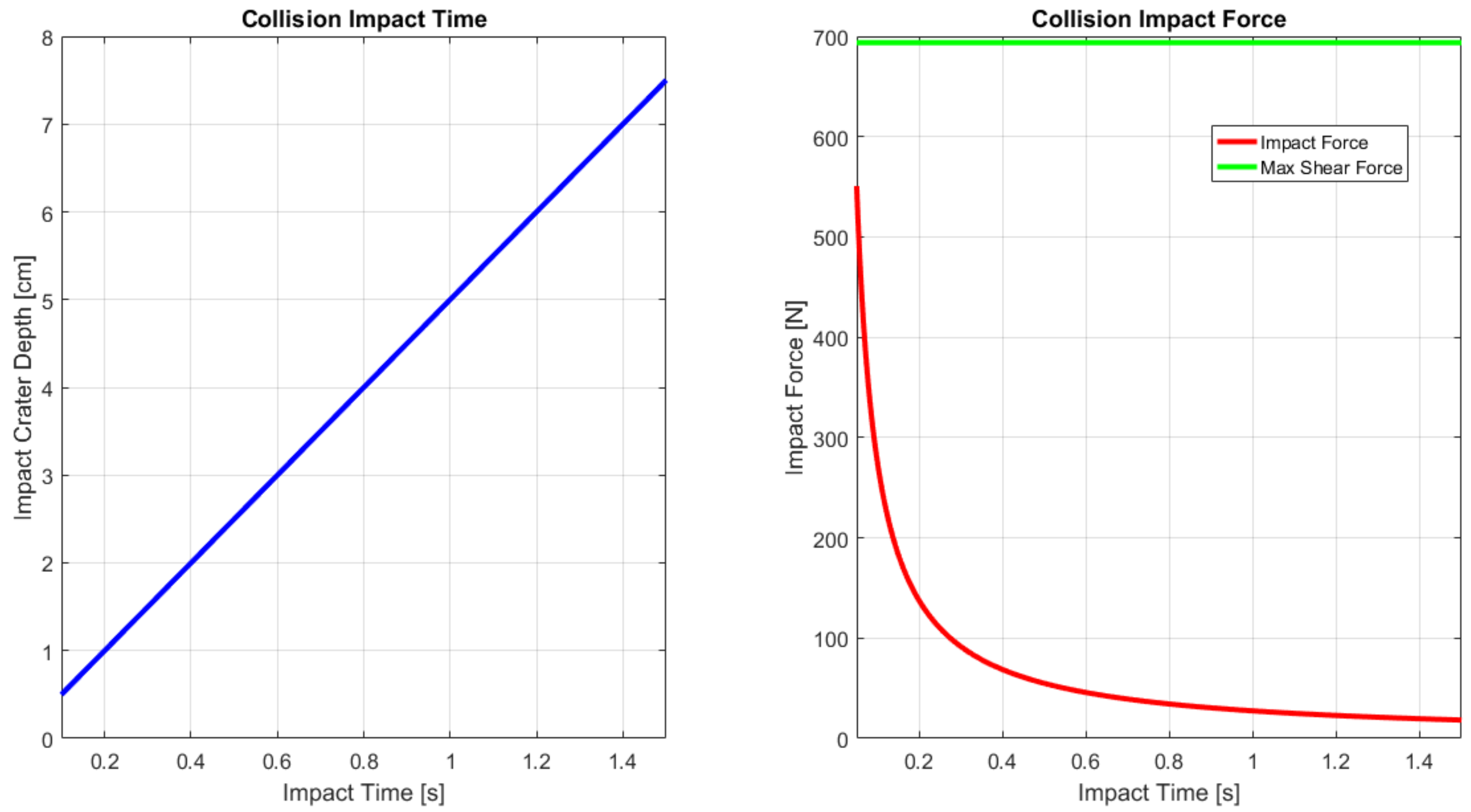




$$P_{impact} = \frac{F_{impact}}{SA_{base}} \Rightarrow \frac{F_{impact,DI}}{SA_{base,DI}} = \frac{F_{impact,CS}}{SA_{base,CS}}$$

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

Impact Collision Calculations



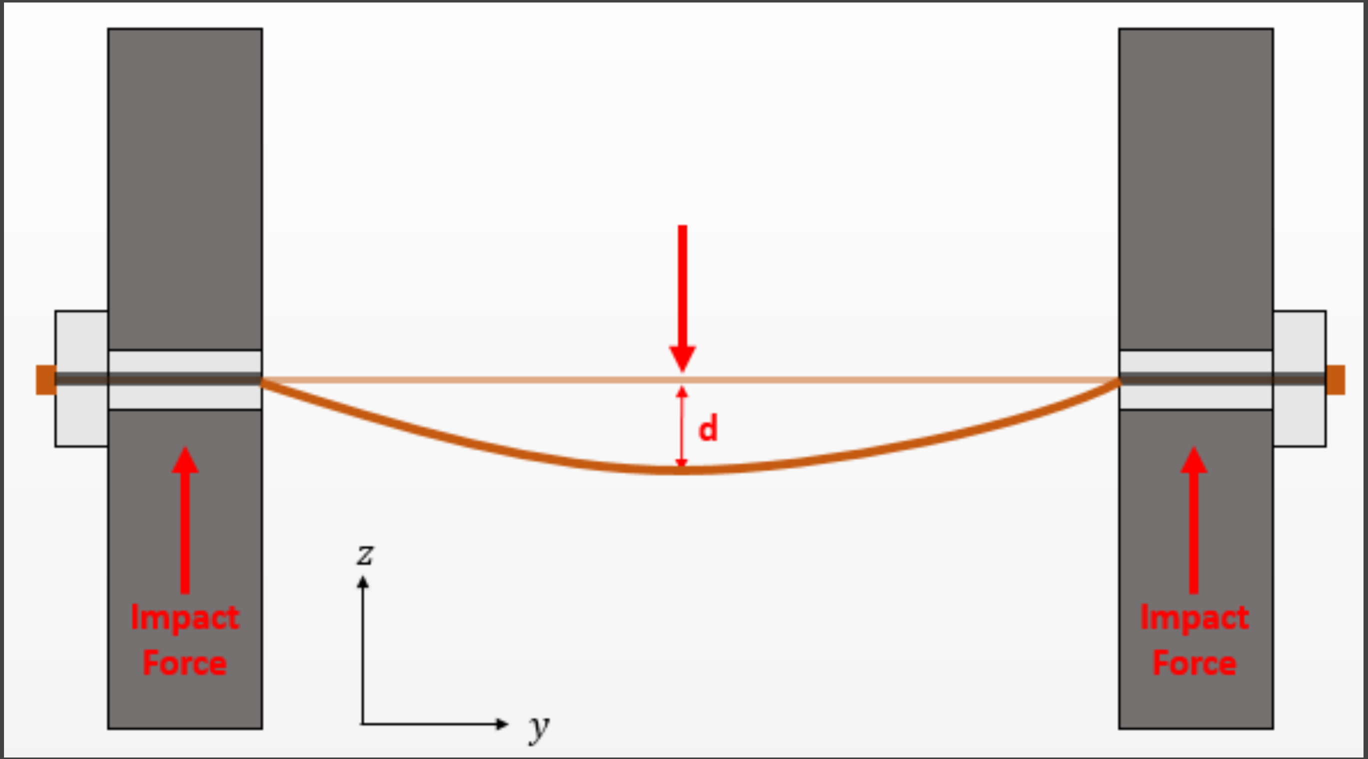
Impact Modeling Test

- In order to determine a number for the force of impact, the time of impact must be known.
- Impact time is difficult to measure without high speed filming capabilities.
- A simple analysis can stem from crater depth (distance needed to stop).
- Assuming constant acceleration:

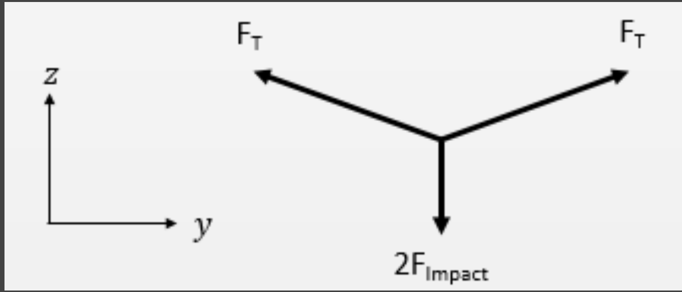
$$t_{impact} = \frac{2d}{v_f + v_i} \rightarrow t_{impact} = \frac{d}{5}$$

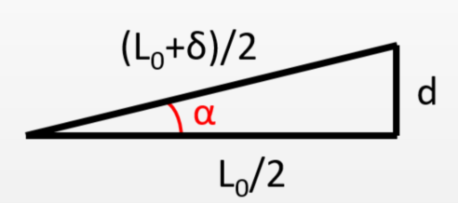
Wire Electrode Impact Analysis

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})

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

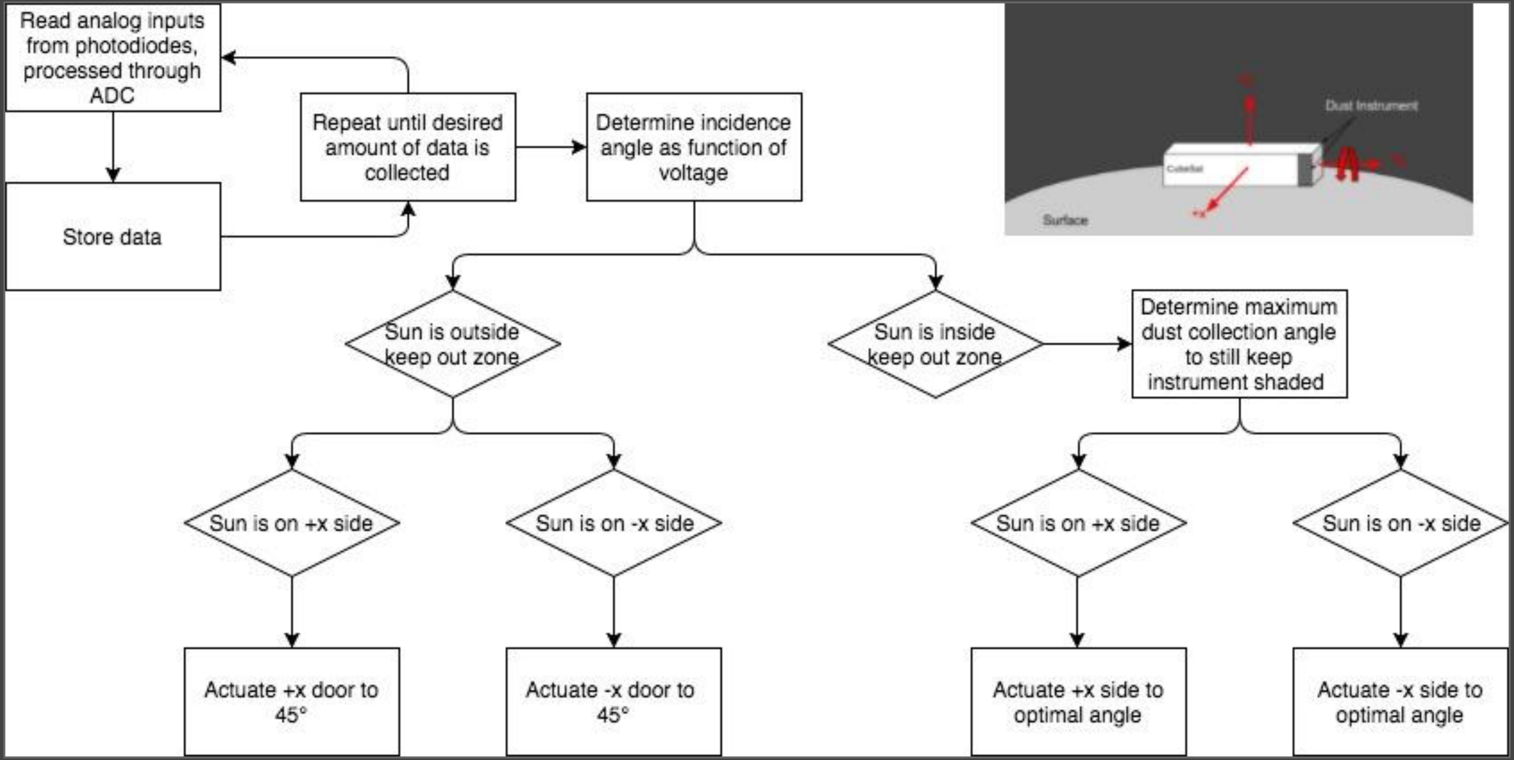
$$\alpha = \sin^{-1}\left(\frac{d}{\frac{L_0+\delta}{2}}\right) = 1.982^o$$

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

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

Software Backup Slides

ARS Software Flow Diagram



Event Trigger Software Cycle Count

Assume a filter, f[n] that is 20 samples in width. The signal is g[n]. So, the cross correlation at time *n* is:

$$c[n] = \sum_{m=1}^{20} g[m] f[m+n]$$

Explanation	Number of instructions	Cycles per instruction	Total Clock Cycles
Load signal and filter for each channel	24 x 40 = 960	2	1920
f[m] g[m+n] multiplication	24 x 20 = 480	1	480
Sum from m = 1 to 20	24 x 20 = 480	1	480
Program control overhead	< 1000	1	< 1000
Worst case			**< 4000**

Event Trigger Software Runtime

The event trigger software requires <4000 clock cycles, so, at a 180 MHz clock speed:

$$t_{\text{trigger}} = \frac{4000\ \text{cycles}}{180 * 10^6\ \text{cycles/s}} = 22.2\mu\text{s}$$

For the ADC:

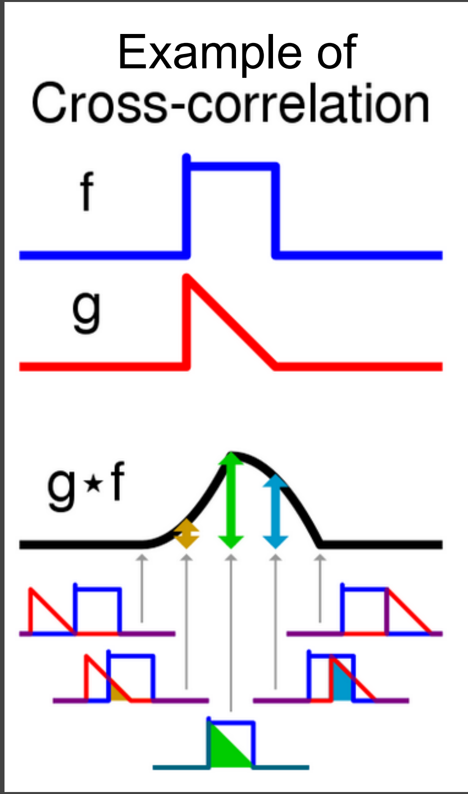
$$t_{\text{conversion}} = 15 * t_{ADC\_clock} = 15 * 0.5\mu\text{s}$$

$$\therefore t_{\text{conversion},24} = 12\mu\text{s}$$

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

$$(f \star g)(t) = \int_{-\infty}^{\infty} \bar{f}(T) g(t+T) dT$$



Trade Study: Door Mechanism

Criteria	**1**	**2**	**3**	**4**	**5**
Mass	≥ 650 g	< 650 g	< 600 g	< 550 g	< 500 g
Cost	≥$175	<$175	<$150	<$125	<$100
Size	≥ 250 cm^3	< 250 cm^3	< 225 cm^3	< 200 cm^3	< 175 cm^3
Mechanical Complexity	-interferes w/ insturment	-≥ 4 actuators -no interference w/ instrument	-3 actuators -no interference w/ instrument	-2 actuators -no interference w/ instrument	-1 actuator -no interference w/ instrument

Criteria	**Weight (%)**	**Options**		
		Hinged	Electromagnet	Sliding
Mass	10	4	1	3
Cost	20	2	4	5
Size	30	3	2	4
Mechanical Complexity	40	2	1	4
Weighted Total	100	2.5	1.9	4.1

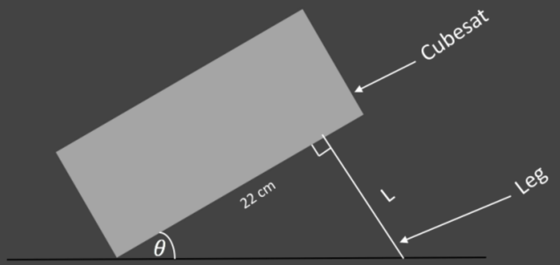
Trade Study: Tilting Mechanism

Criteria	**1**	**2**	**3**	**4**	**5**
Number of Actuators	8 actuators	4 actuators, also requires gears	4 actuators	2 actuators, legs are jointed	2 actuators
Difficulty to design and implement	100% custom design, interferes with door	100% custom design, no door interference	COTS & custom design, interferes with door	COTS & custom design, no door interference	COTS, no door interference
Volume Required	>1000 cm^3	750-1000 cm^3	500-750 cm^3	250-500 cm^3	<250 cm^3
Mass	>3 kg	2.3-3 kg	1.6-2.3 kg	1-1.6 kg	<1 kg
Cost	>$900	$650-$900	$400-$650	$150-$400	<$150

Criteria	**Weight (%)**	**Options**				
		Telescoping Legs	Lever Arm	Scissor Lift	Jointed Arm	Gear Rack
Number of Actuators	25	2	5	4	1	2
Difficulty to design/implement	25	1	4	3	1	4
Volume Required	20	1	3	5	2	2
Mass	10	1	4	5	2	4
Cost	20	3	4	5	4	1
Weighted Total	100	1.65	4.05	4.25	1.9	2.5

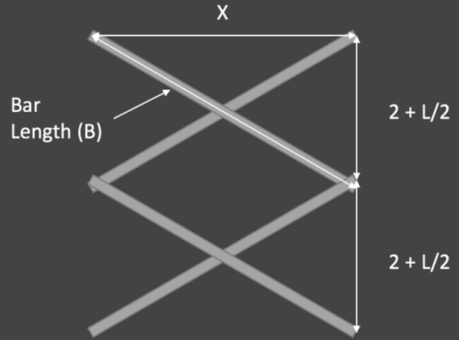
Scissor Lift Tilting Increment

First Need To Determine Length of Leg → Then Need To Determine Horizontal Actuation → Finally, determine motor turning accuracy



$$L = 22 * \tan(\theta)$$

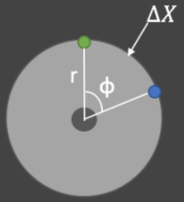
θ = Tilt Angle



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

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

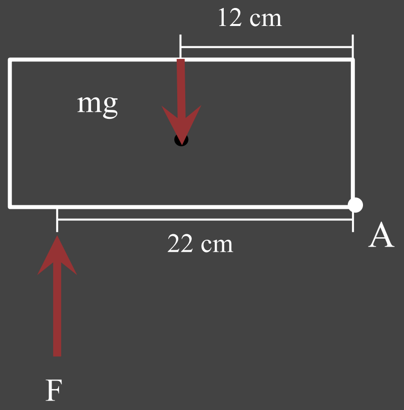
Horizontal Actuation = $\Delta X = X - X'$



Motor Turning Angle

$$\Phi = \frac{360° * \Delta X}{2 * \pi * r}$$

Tilting Mechanism Force Calculations



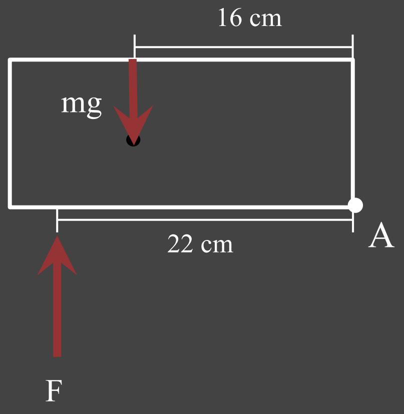
- Assume center of mass is at the center of the CubeSat

$$\sum M_A = F(0.22) + mg(0.12) = 0$$

$$F = \frac{mg(0.12)}{0.22}$$

$$F = \frac{(0.1)(9.81)(0.12)}{0.22} = 0.545\ N$$

Tilting Mechanism Force Calculations: Maximum



- Assume center of mass is at the maximum distance from the pivot

$$\sum M_A = F(0.22) + mg(0.16) = 0$$

$$F = \frac{mg(0.16)}{0.22}$$

$$F = \frac{(0.1)(9.81)(0.16)}{0.22} = 0.713\ N$$

$$\tau = F(0.22) = 0.713(0.22) = 0.157\ N\,m$$

Motor Torque/Force

Motor Torque: 1.5 N m

1 cm radius

$$F = \frac{\tau}{r} = \frac{1.5}{0.01} = 150N$$

1.5 cm radius

$$F = \frac{\tau}{r} = \frac{1.5}{0.015} = 100N$$

2 cm radius

$$F = \frac{\tau}{r} = \frac{1.5}{0.02} = 50N$$

F > 0.73 N → Feasible

Leg Volume and Mass Calculation

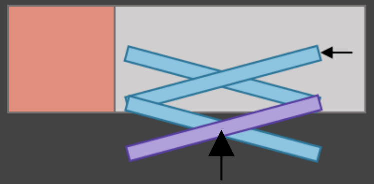
Leg Dimensions: 2 x 16 x 0.3175 cm ⇒ 10 cm^3

Number of Bars: 4

Density of Aluminum: 2.70 g/cm^3

$$\rho = \frac{m}{V}$$

Where m is mass and V is volume



$$m = \rho V$$

$$m = (2.70)(10)$$

$$m = 27g = 0.027kg$$

$$m_l = 4m$$

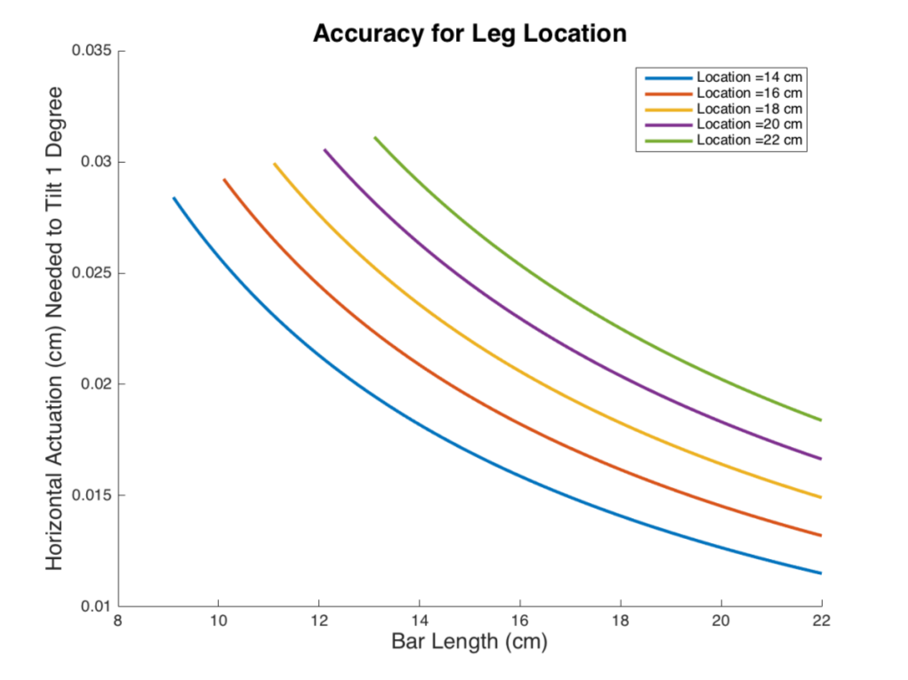
$$m_l = 4(0.027) = 0.110\ kg$$

$$m_t = 2m_l$$

$$m_t = 2(0.110) = 0.220\ kg$$

Leg Location Determination

- Need less accurate actuation the farther out the leg is from tilting edge.
    - Makes tilting easier further out leg is.
- The farther the leg is, the more room we have to work with.



Possible Locking Mechanisms

- Solenoid Brake
  - Small
  - Inexpensive
  - Works with servo motor

- Worm Gear Box
  - Larger in size and mass
  - Expensive
  - Would require stepper motor

Both methods are feasible and meet all requirements

Mass and Volume

1.1.2. The ARS shall take up less than 3U of the CubeSat model's interior.
1.2.1. The combination of the ARS, sensor processor and CubeSat model shell shall have a maximum mass of 7.84 kg.

Component	Mass (kg)	Volume (cm^3)
Leg Motors	0.11	346
Legs	0.22	81
Door Motors	0.11	346
Door Mechanisms	0.069	26
ARS Microcontroller	0.05	40
Instrument Microcontroller	0.05	100
Shell	2.5	1000
Total	**3.109**	**1939**

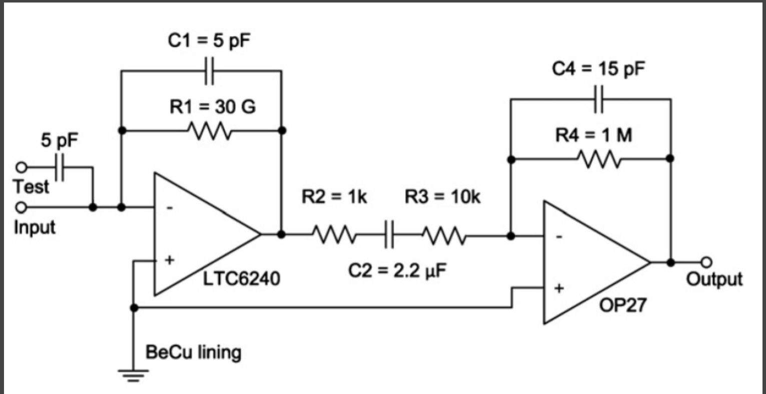
Available Mass: 7.84 kg

Margin: 4.73 kg → **Feasible**

Available Volume: 3U = 5073.5 cm^3

Margin: 3134.5 cm^3 → **Feasible**

CSA Circuit (Given)

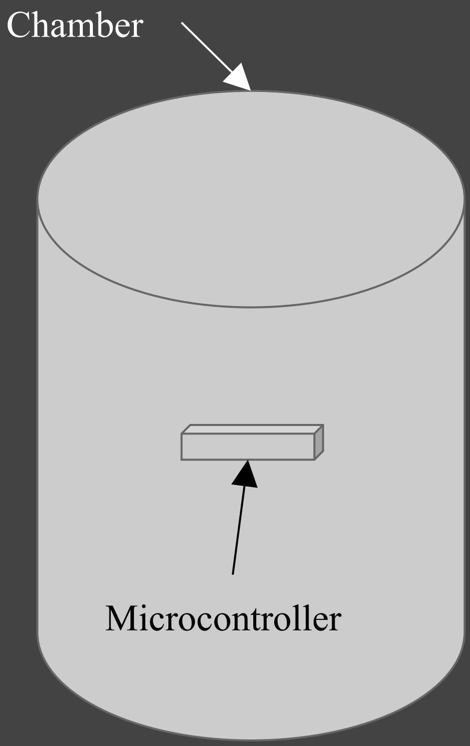


- Given by the client as a low noise method to translate a charge induced on a wire electrode into an amplified voltage
- The first op-amp is a charge sensitive preamplifier with gain of 1/C1
- Second is an AC coupled voltage amplifier with a gain of 91

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

→ ADC resolution will be much greater than needed

Thermal



Assumptions:

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

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

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

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

$$T_{micro} = 301.7K$$

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