QB50 CubeSat CDR

STAR

Satellite Testbed for Attitude Response

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Presentation Outline

Project Overview

- Mission Overview
- Mission Objectives
- CONOPS

Interface Board

- Requirements
- FBD
- CPE
- Design
- Testing

Sun Sensor Turn-table

- Requirements
- FBD
- CPE
- Design
- Testing

Helmholtz Cage test apparatus

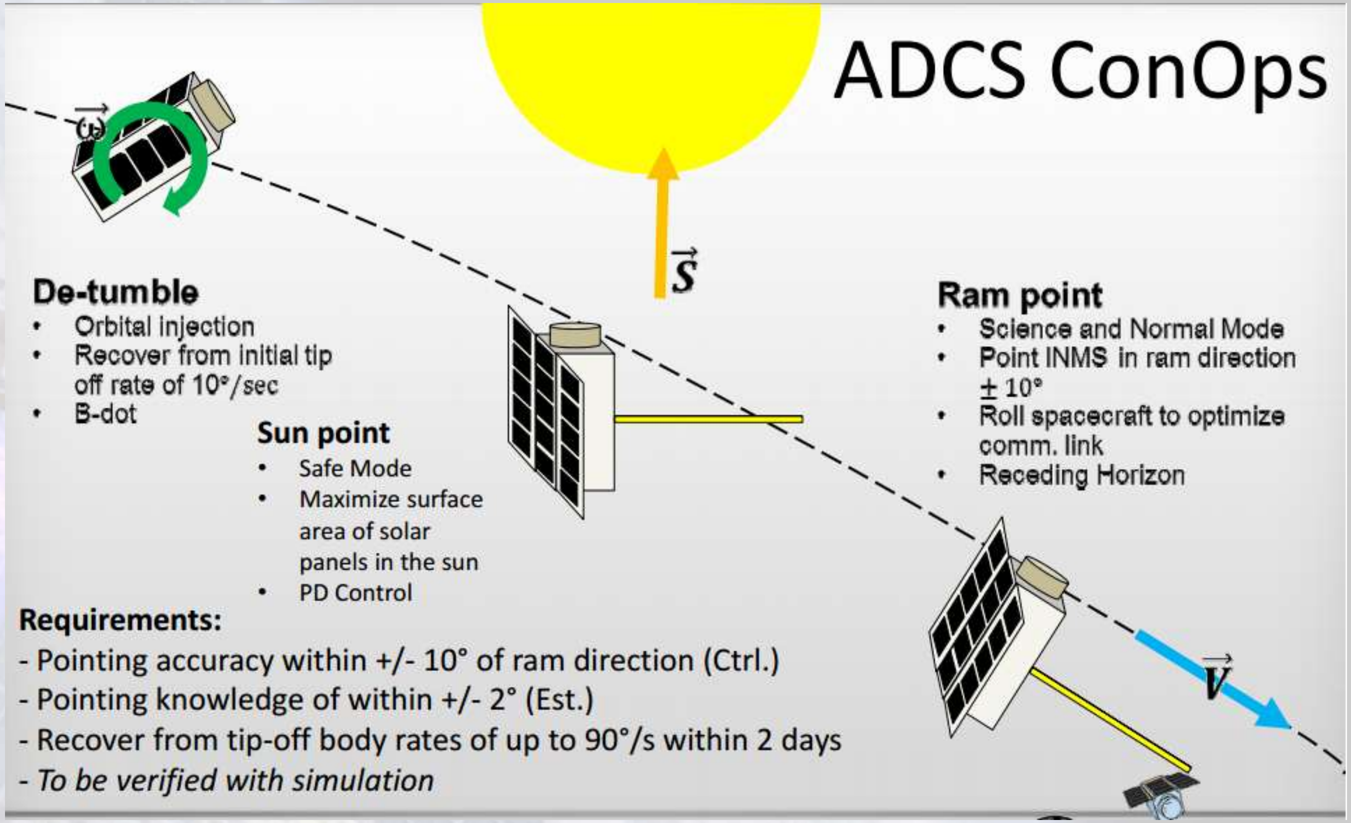
- Requirements
- FBD
- CPE
- Design
- Testing

Status Summary

- Design Summary
- Risks
- WBS
- Budget
- Test Plan
- Schedule

Mission Overview

- QB50 Overview
  - 1 of 50 CubeSats worldwide
  - Low budget, scientific research
  - CubeSats vary in sizes (1U, 2U, 3U)
  - Attitude Determination and Control System (ADCS)
    - 15 Sun Sensors
    - 3 Magnetometers
    - 2 Rate Gyros
    - GPS



Problem Statement

Develop a **test suite** that will allow for the **validation and calibration** of the QB50 Attitude Determination and Control System based (**ADCS**) on simulated mission environment.

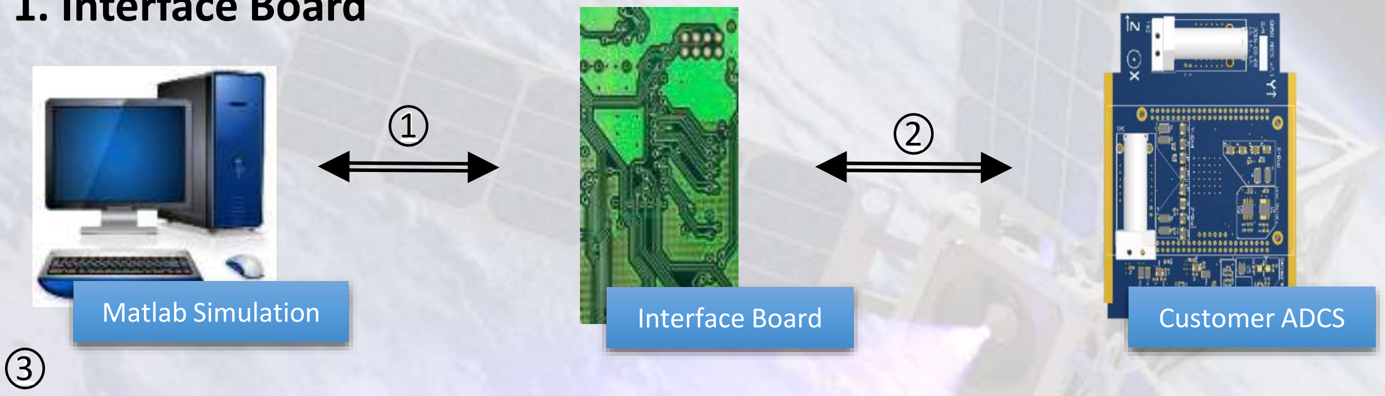
Project Objectives

- Develop an ***interface board*** that will allow for a hardware-in-the-loop simulation by running a simulation on the ADCS board.
- Develop a ***turn-table*** apparatus for Sun sensor calibration.
- Develop ***test apparatus*** for conducting Helmholtz cage test.

Concept of Operations

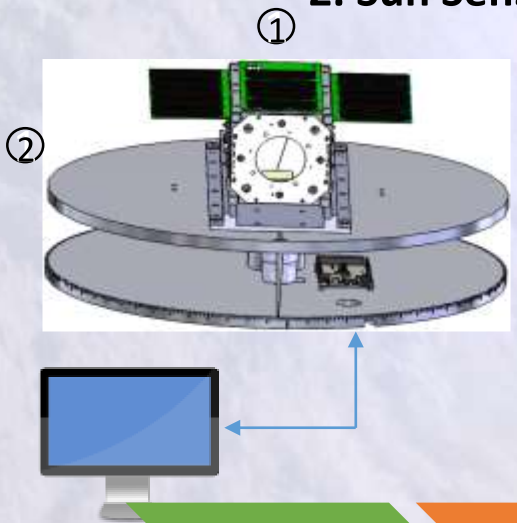
- Develop 3 **individual** tests, listed in priority

1. Interface Board



1. Connect simulation to interface board
2. Connect interface board to ADCS
3. Run Simulation and log data

2. Sun Sensor Turntable



1. Integrate CubeSat
2. Rotate turntable
3. Compare table angle to angle reported by CubeSat

③

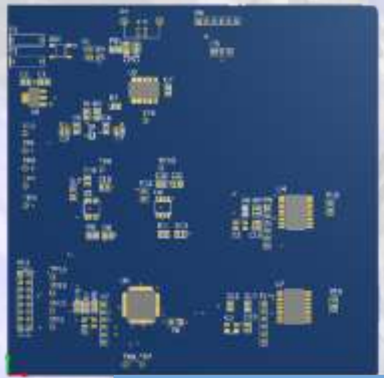
3. HelmHoltz Cage test

1. Integrate CubeSat
2. Rotate CubeSat
3. Verify functionality of magnetorquer

Interface Board

Matlab Simulation

↔



Interface Board

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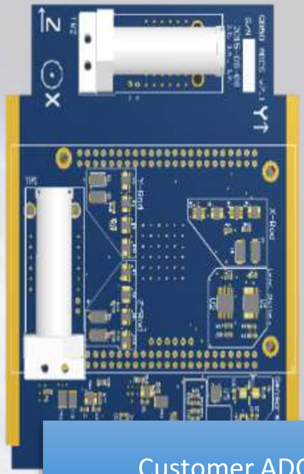
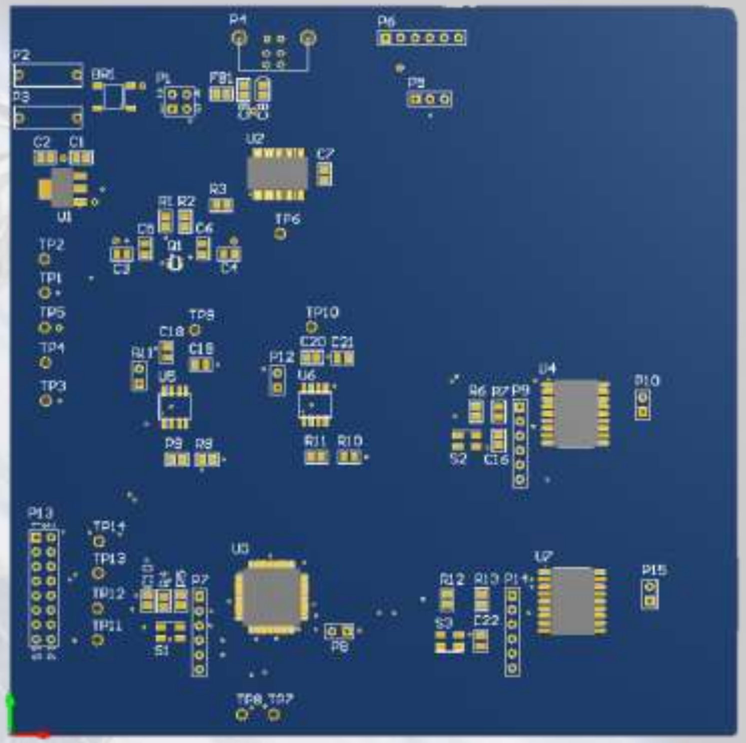


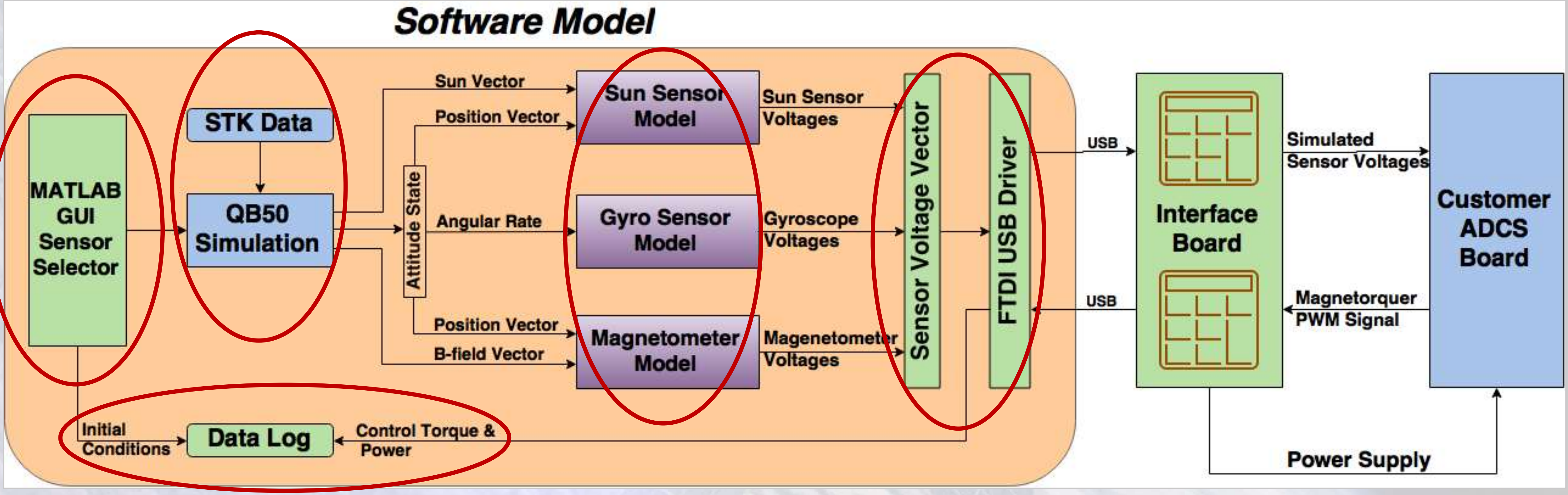
Customer ADCS

Critical Project Elements – Interface Board

- Transmit sensor data from Matlab simulation to ADCS
- Measure ADCS response
  - Capture magnetorquer PWM signals
  - Accuracy of 10% or greater
- Measure ADCS power draw
  - Measure current and voltage of 3.3V supply
  - Measure current and voltage of 5V supply
  - Accuracy of 5% or greater
    - Applies to current and voltage



Simulation Model FBD



Customer Provided

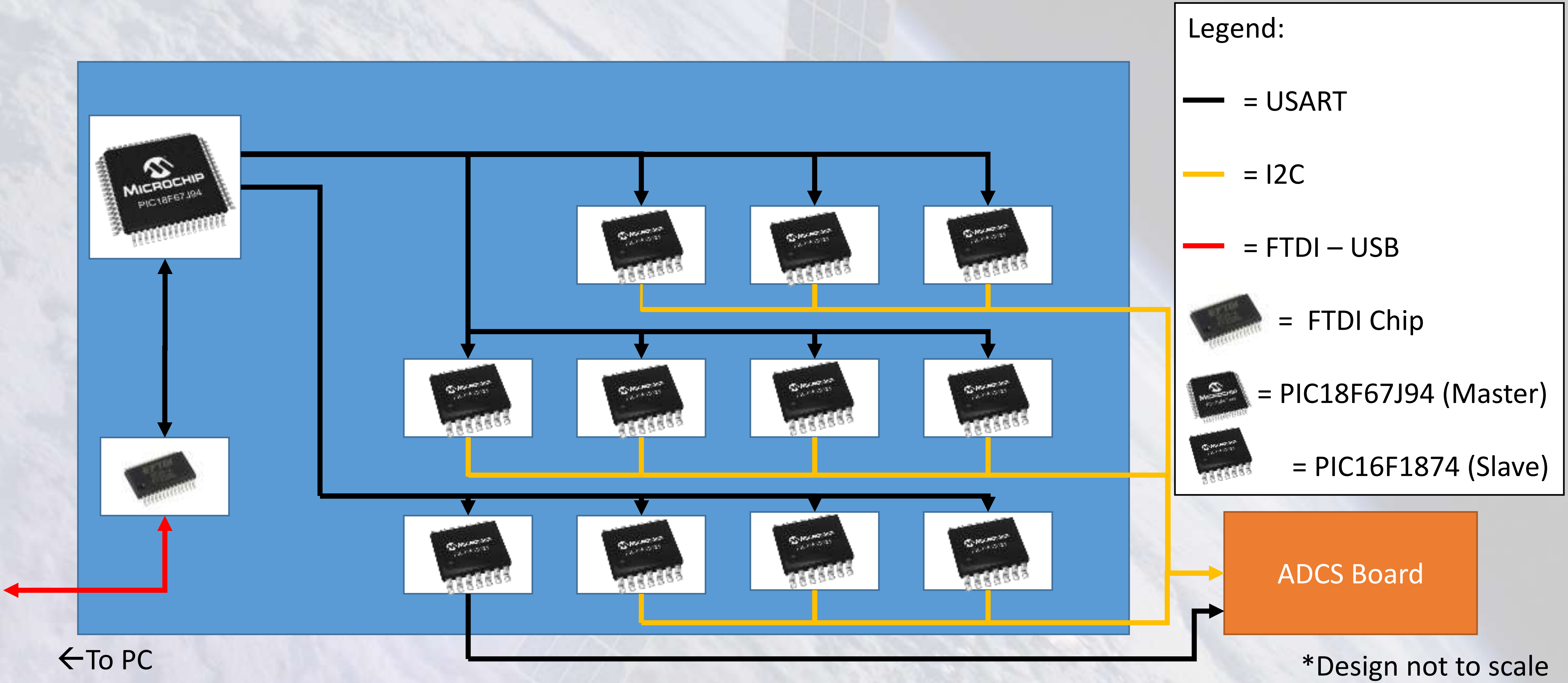
Team STAR developed

Modified QB50 Sim

Nomenclature

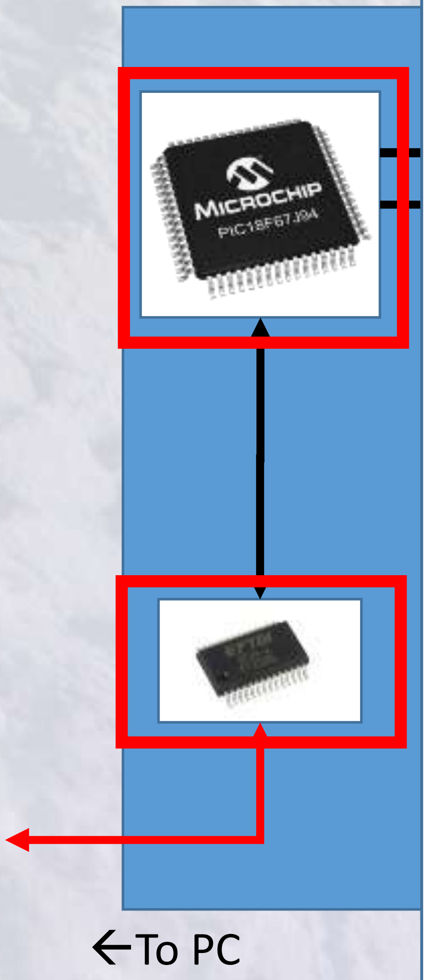
- UART - Universal Asynchronous Receiver/Transmitter
- EUSART - Enhanced Universal Synchronous/Asynchronous Receiver/Transmitter
- ADC - Analog to Digital Converter
- CCP - Capture/Compare/PWM
- PWM - Pulse Width Modulation
- MSSP - Master Synchronous Serial Port
- I2C - Inter-Integrated Circuit

Interface Board Data Flow/Connections



*Design not to scale

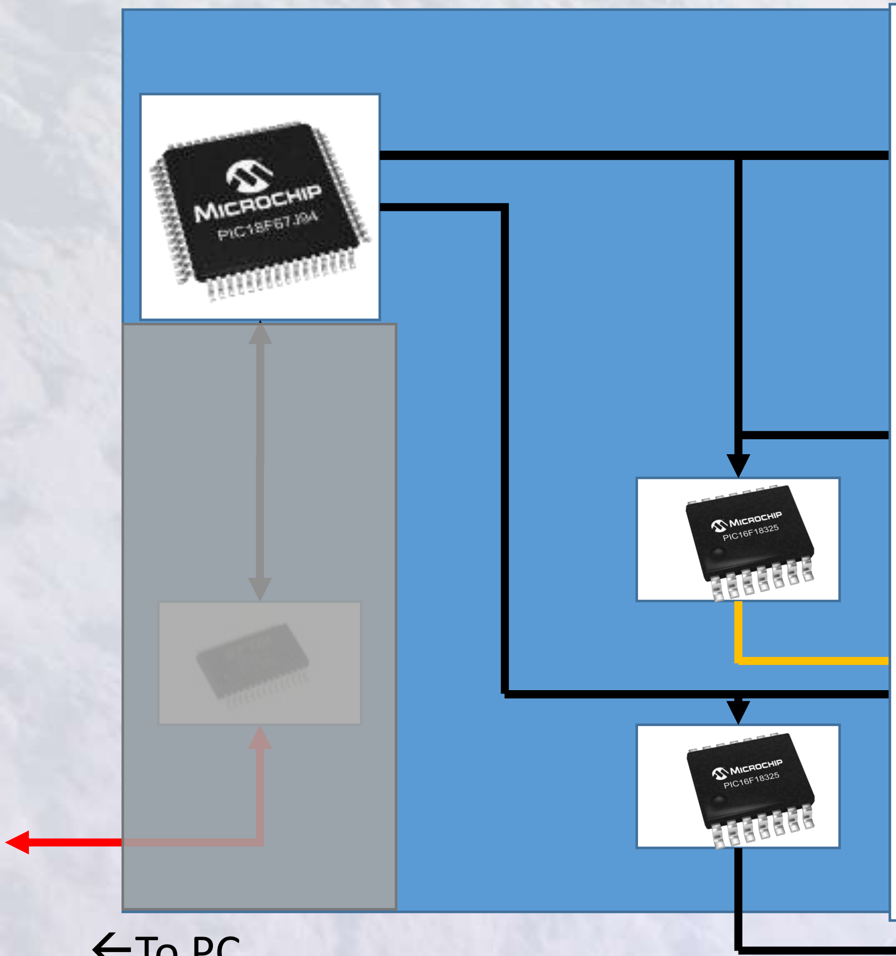
Interface Board Data Flow/Connections



Master Microcontroller – PIC18F67J94

- Use internal oscillator @ 8MHz
- 2 EUSART modules used
  - Receive data from FTDI cable
  - Send data to slave microcontrollers
- 4 of 24 ADC channels used to measure voltage and current
  - Measure between 0V and 3.3V
- 3 of 7 CCP modules used to capture 3 magnetorquer PWM signals

Interface Board Data Flow/Connections



←To PC

Slave Microcontrollers – **PIC16F18325**

- 1 EUSART module used to receive data from master microcontroller
- Both MSSP modules (configured for I2C) used to emulate ADCS sensors

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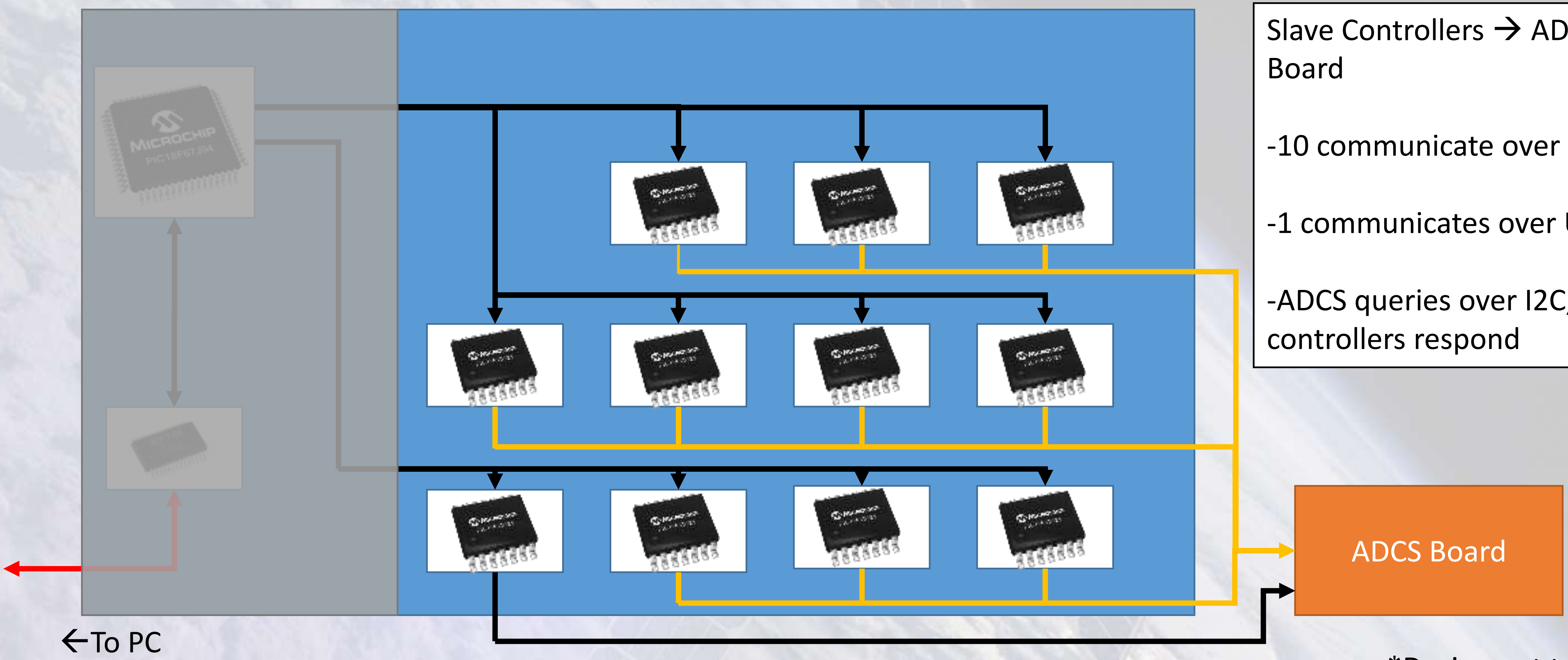
Interface Board Data Flow/Connections



Slave Controllers → ADCS Board

-10 communicate over I2C

-1 communicates over USART

-ADCS queries over I2C, Slave controllers respond

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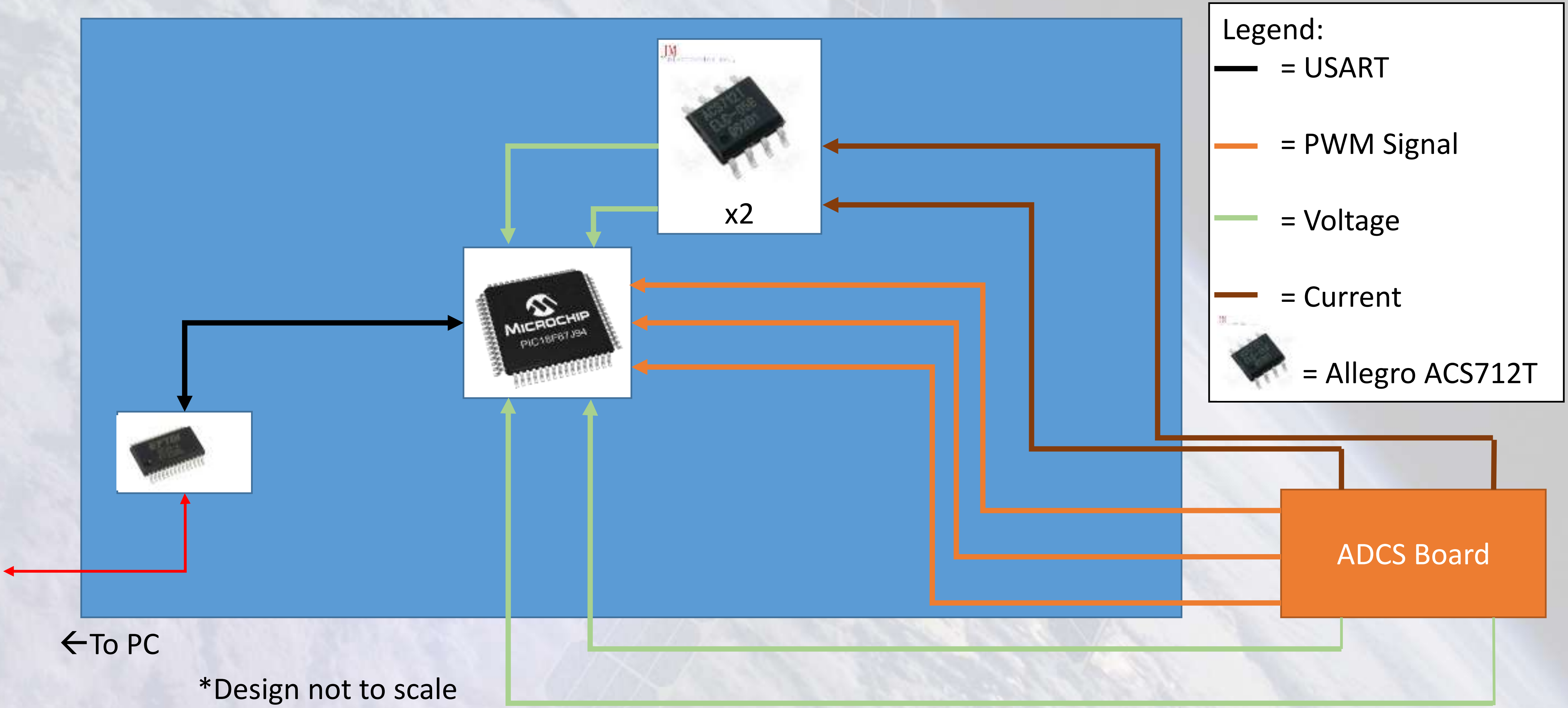
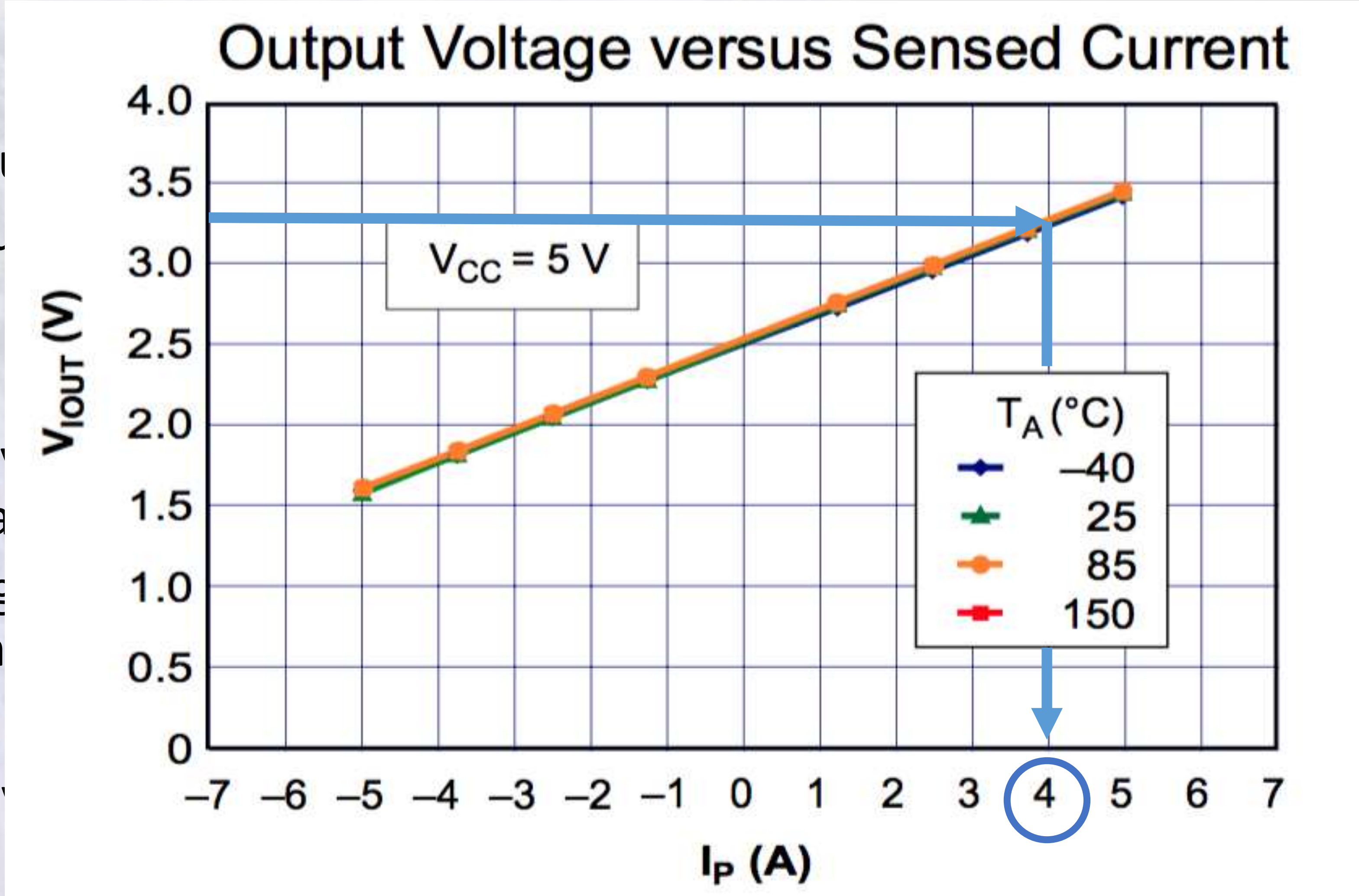
Interface Board Data Flow/Connections from ADCS



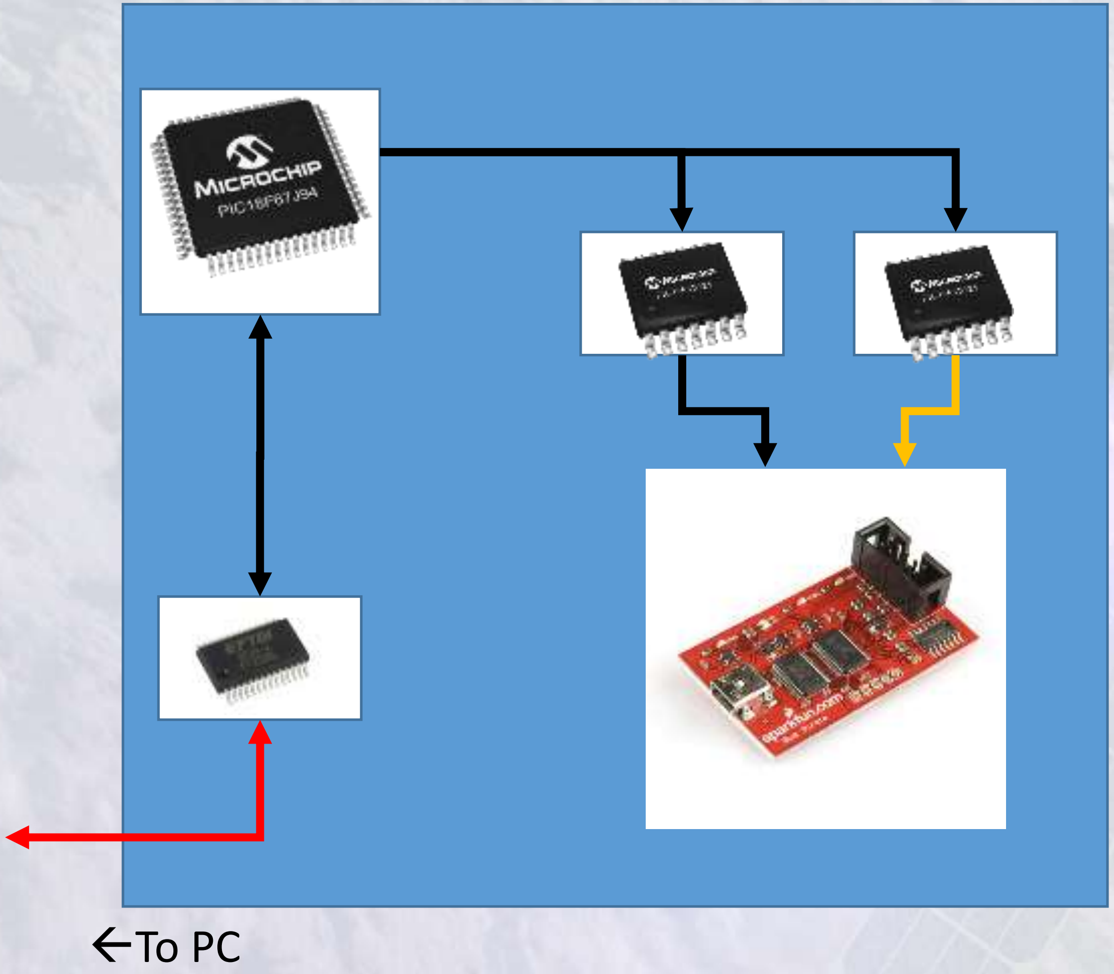
ADCS Power Measurement

- Current
  - Measu
  - Outpu and 5
- Voltage
  - Supply by ma
  - Voltag the m

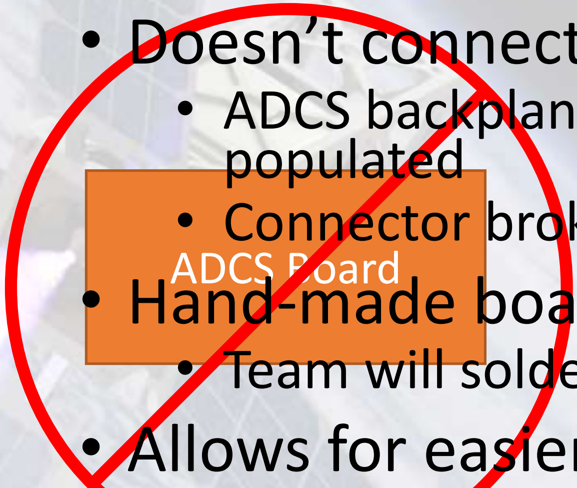


* ADC input

Validation: Testing Board



- Lacks full set of slave microcontrollers
- Doesn't connect to ADCS board
  - ADCS backplane connector not populated
  - Connector broken out to header
- Hand-made board
  - Team will solder connections
- Allows for easier probing of pins
  - Verify step-by-step data flow
  - Lots of test pins
  - Enable jumpers for various components



Legend:

= USART

= I2C

= FTDI – USB

= FTDI Chip

= PIC18F67J94 (Master)

= PIC16F1874 (Slave)

= Bus Pirate

*Design not to scale

Digital Data - Validation

- Bus Pirate
  - Used to query slave microcontroller data over I2C
  - Off-ramp - Microavionics Board

- Digital Logic Analyzer
  - Capture UART data being transmitted and validate it is correct

Current and Voltage Measurements - Verification

Resolution

- 12-bit ADC
- 0V-3.3V Range

$$3.3/_{2^{12}} = 0.81\text{mV resolution}$$

- Current sensor sensitivity of 185 mV/Amp

$$0.81/_{185} = 4.4\text{mA resolution}$$

Errors

- Current sensor error = 1.5%
- Effective resolution due to noise:

$$\log_2\left(\frac{2^N}{RMS\ input\ noise\ (LSB)}\right) = 10\text{–bits}$$

- Resolution error = .098%

Total error = 1.5% meets 5% requirement

Current and Voltage Measurements

Validation

- Use oscilloscope and digital multimeter to measure actual voltage and current
- Compare with measured voltage and current

PWM – Duty Cycle Calculations

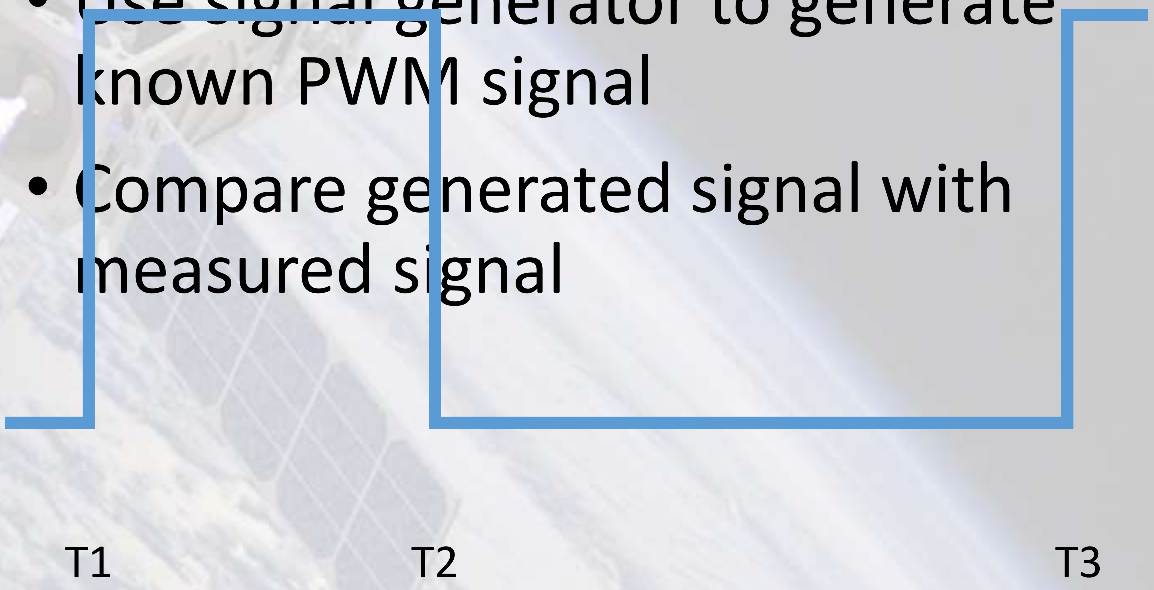
Time measurement error is 1.5% based on internal oscillator error

$$Duty\ Cycle = \frac{T2\ - T1}{T3\ - T1}$$

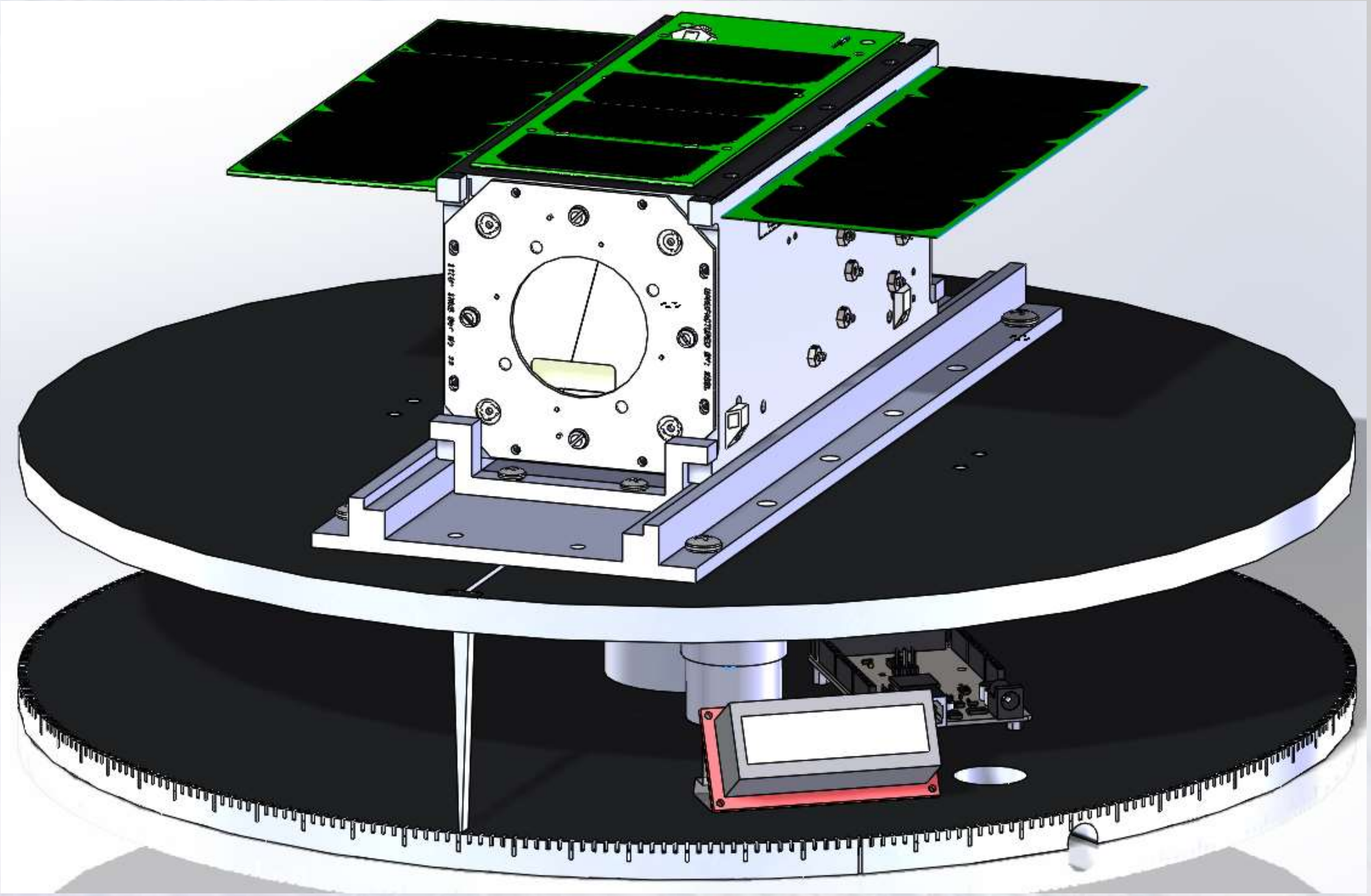
Total error is 3% (meets 10% requirement)

Validation

- Use signal generator to generate known PWM signal
- Compare generated signal with measured signal



Sun Sensor Turntable



Mission Introduction → Project Description → Interface Board → Sun Sensor Table → Helmholtz Cage Test → Status Summary

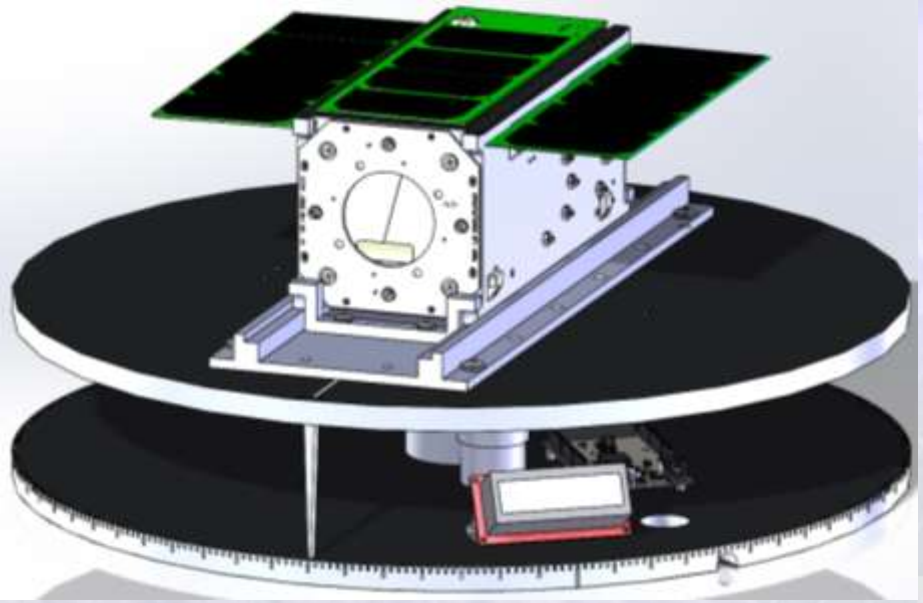
Design Requirements and CPEs - Turntable

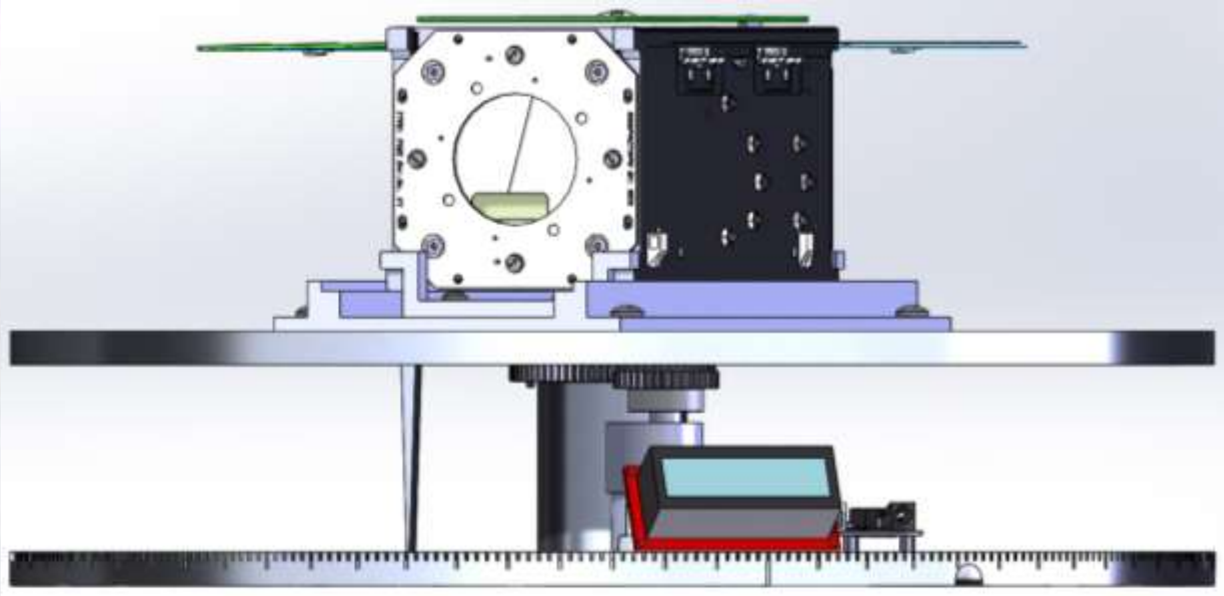
Design Requirements:

1. Sense angular position with a resolution of 1° with ±0.5˚ accuracy
2. Display angular position to user
3. Reflectance < 5% for table top, < 20% for clamps

CPEs:

1. Provide assurance in accuracy of angle position
2. Rotate with RPM such that 10 Hz Sun sensors sample at least once per degree
3. Manual and automatic operation

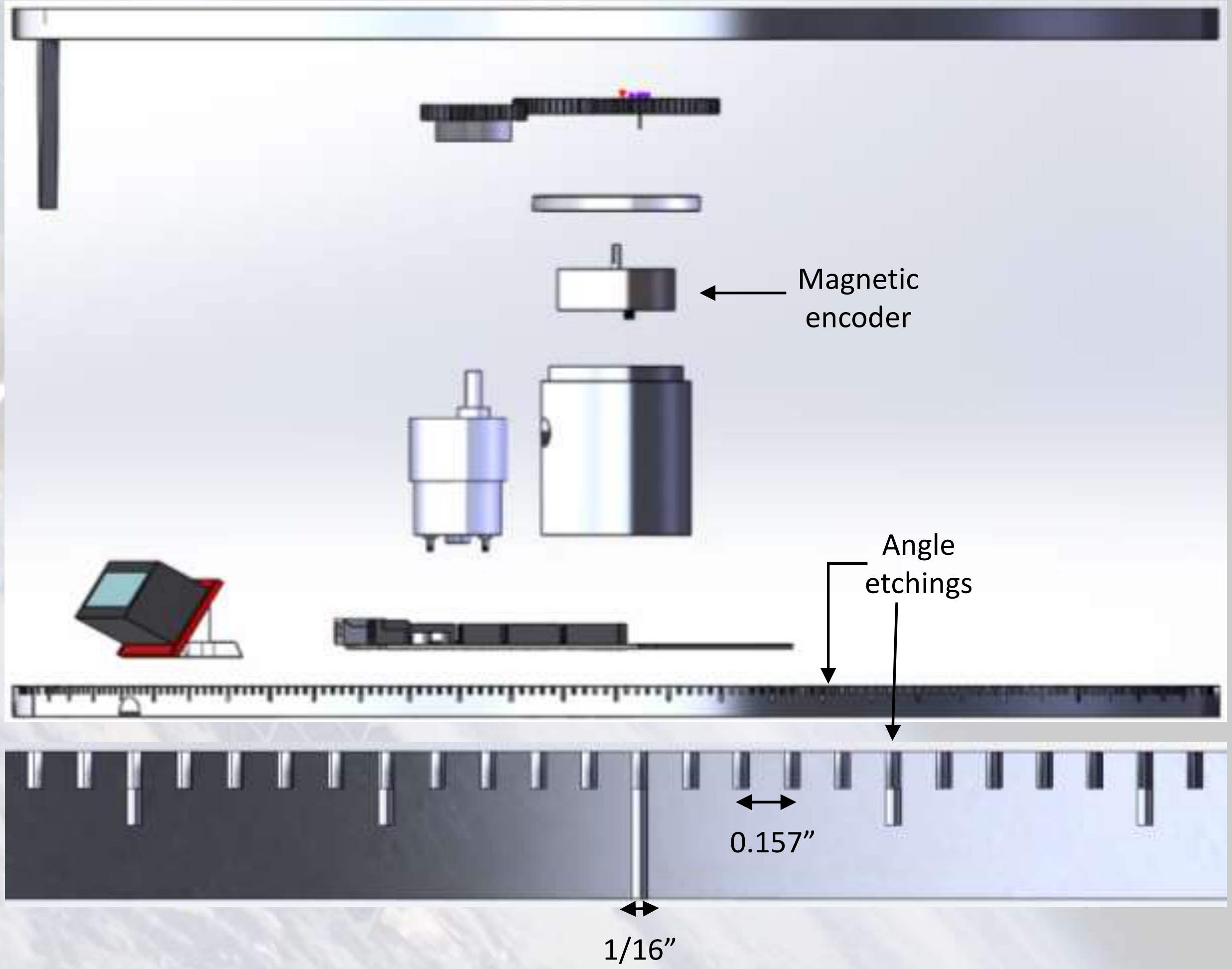




Requirements Solutions - Turntable

1. Sense angular position with a resolution of 1° with ±0.5˚ accuracy
   - 12 bit magnetic rotary encoder
     - Resolution = 360°/2^{12}
       = 0.088° per bit < 1°
     - Rotation shaft of encoder fits into slot on bottom of top board
   - Angle etchings
     - Provide physical-electronics redundancy
     - Board diameter = 18”
     - Etching spacing = circumference/360
       = 0.157”/etching

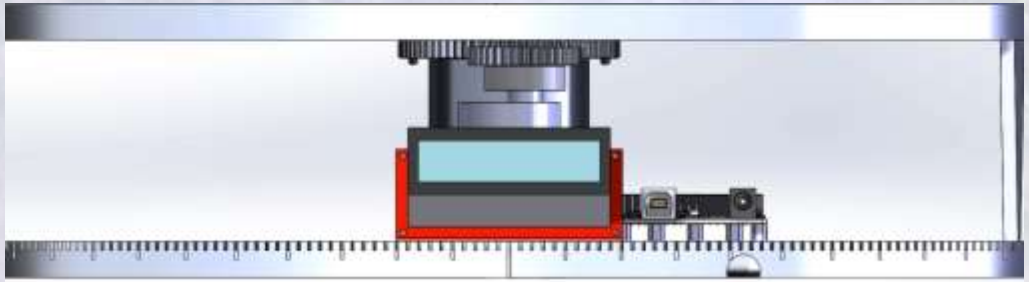
Magnetic Encoder

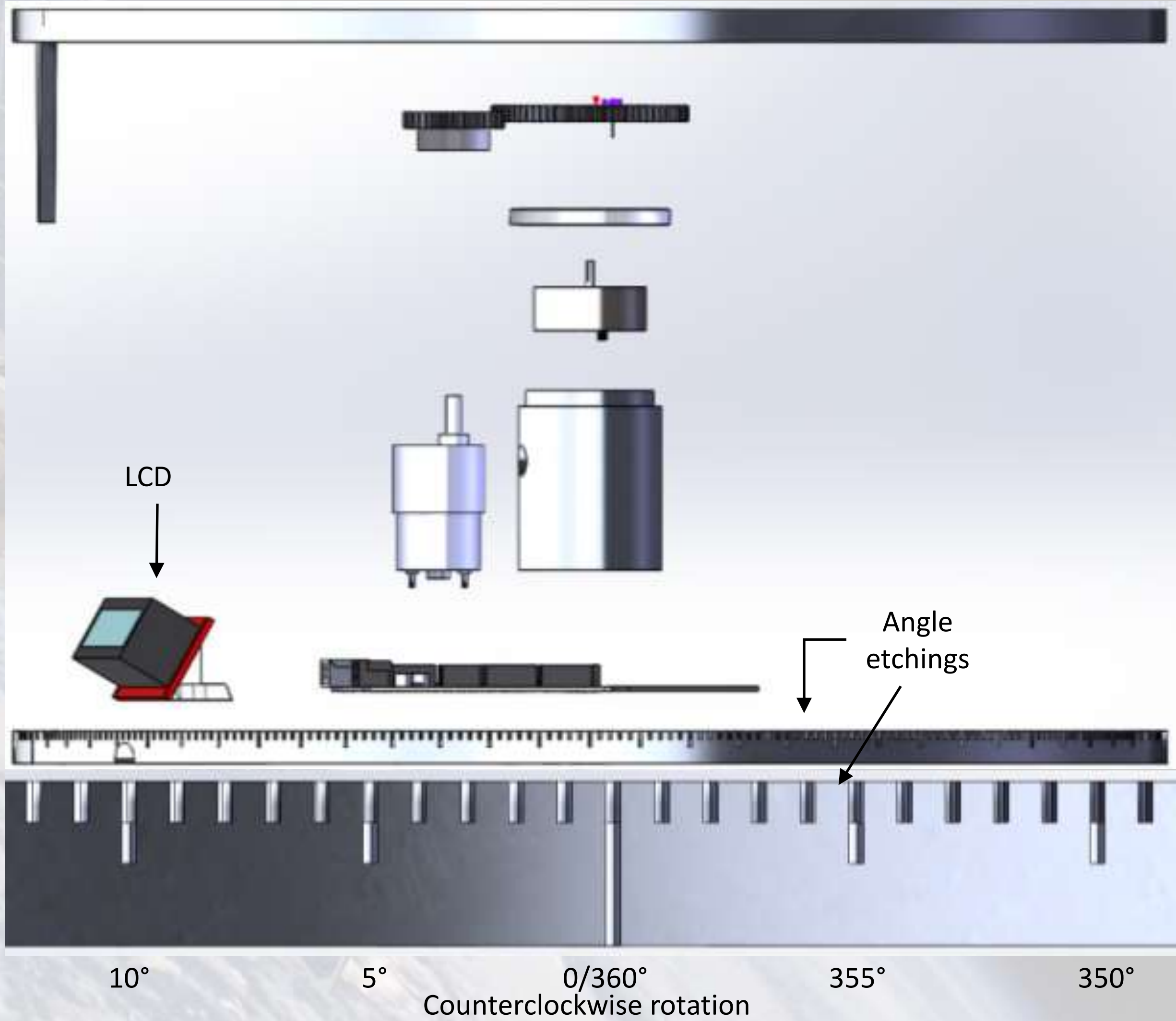


Turntable: Requirements Solutions

2. Display angular position to user
    - LCD display output
        - Arduino to provide analog to digital conversion from encoder
    - Angle etchings
    - Save .txt file with angle, rate, and time

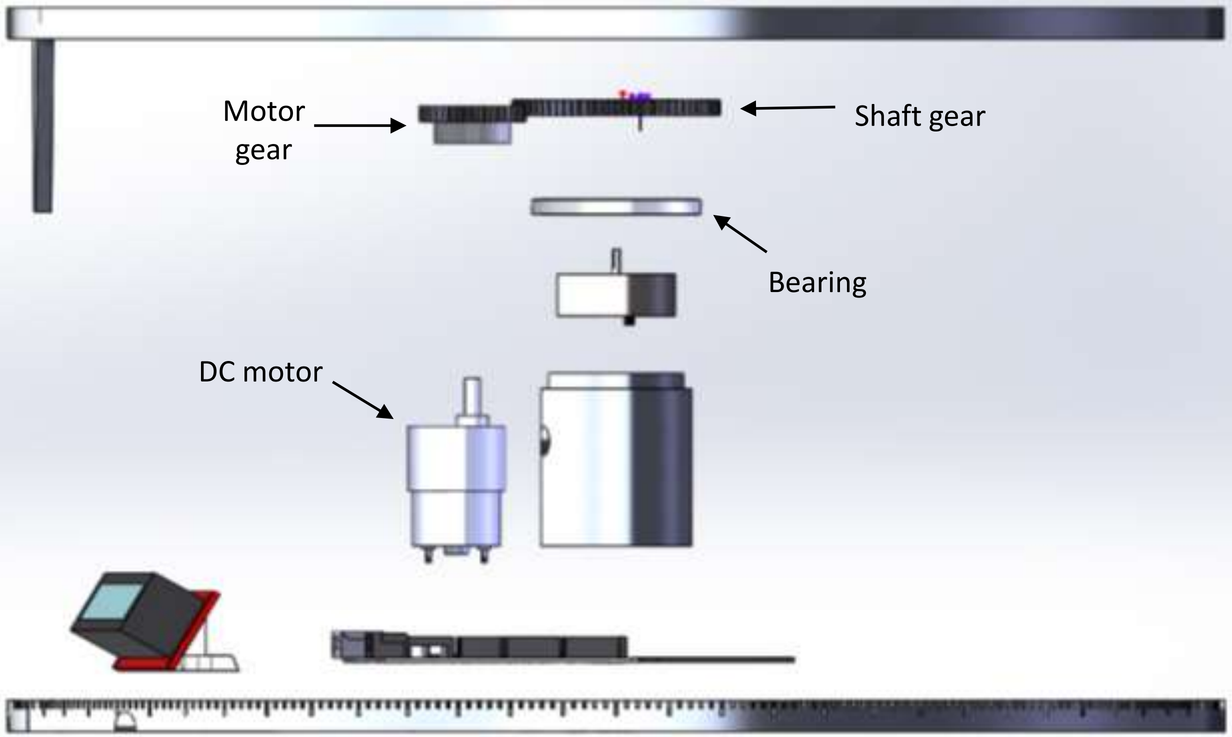
LCD

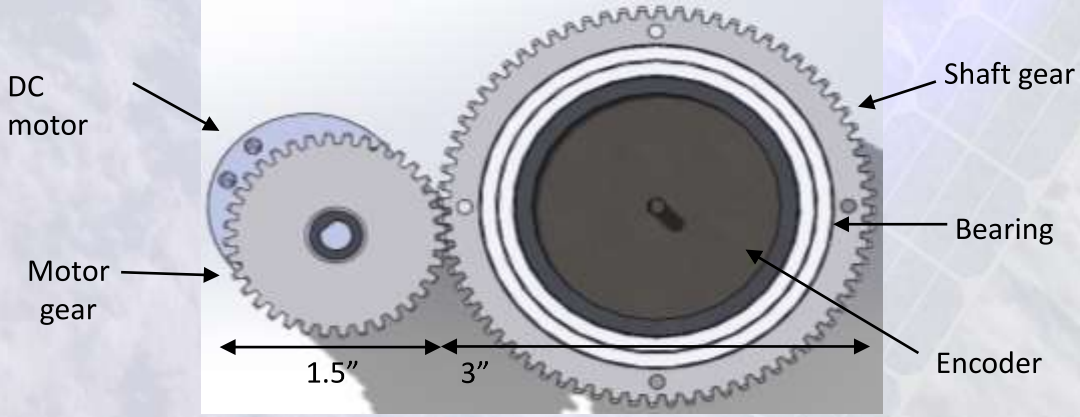




Turntable: Requirements Solutions

3. Manual and automatic operation
   - DC motor, gears, and bearing
     - Friction fit gears and bearing
     - Shaft gear screwed into top board
   - Torque required = 0.29 in*lbs
     - DC motor torque = 187.2 in*lbs (3000:1 internal gear ratio)
     - 2:1 shaft to motor gear ratio
     - Torque produced on board = 374.4 in*lbs





τ_R = torque required on board
r = radius of board
C_f = bearing coefficient of friction
g = gravity
m_t = total mass

$$\tau_R = C_f * m_t * g * r \approx 0.29\ in * lbs$$

Turntable: CPE Solutions

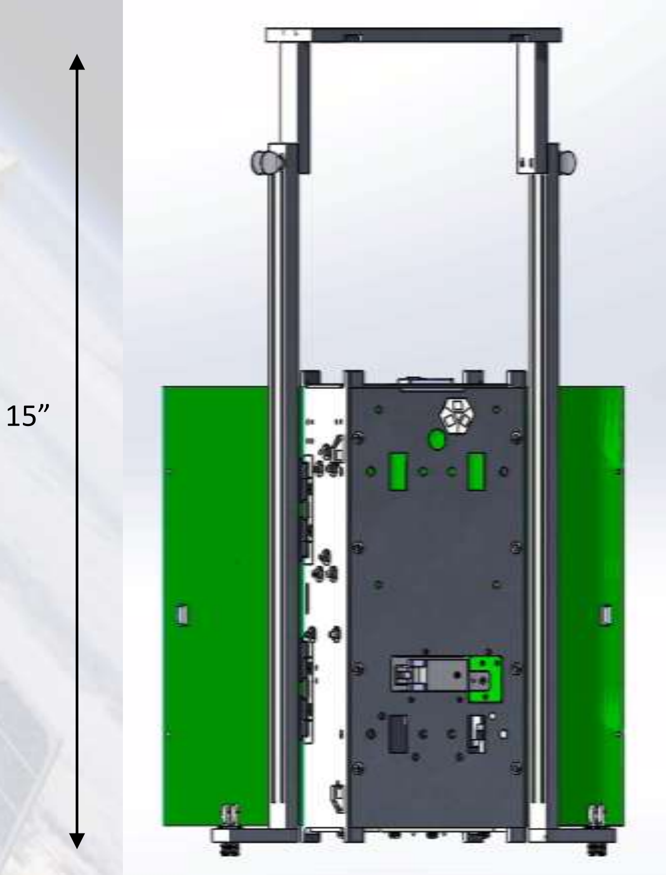
1. Provide assurance in accuracy of angle position
   - Encoder and angle etchings
2. Rotate with RPM such that 10 Hz Sun sensors sample at least once per degree
   - 1 sample per degree = 5/3 RPM

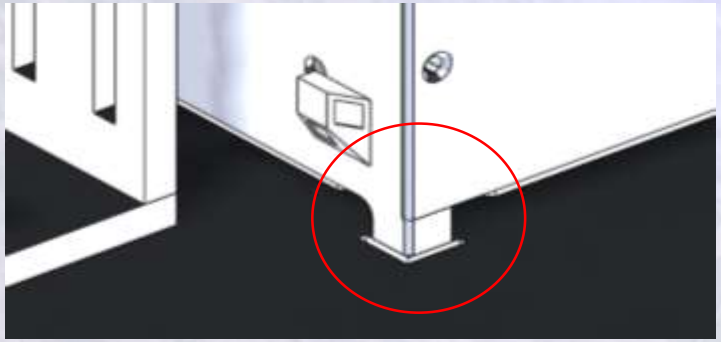
$$RPM_{shaft} = RPM_{motor} * \frac{Teeth_{motor}}{Teeth_{shaft}} = 1 * \frac{36}{72} = \frac{1}{2} < \frac{5}{3}$$

   - Adjust duty cycle of PWM signal to achieve desired RPM ($0 < RPM_{desire} \leq 1/2$)
3. Reflectance < 5% for table top, < 20% for clamps
   - Coat top board in Avian Black-S, reflectance = 3.1%
     - Manufactured by Avian Technologies LLC
   - Sandblast clamps, reflectance = 15-20%

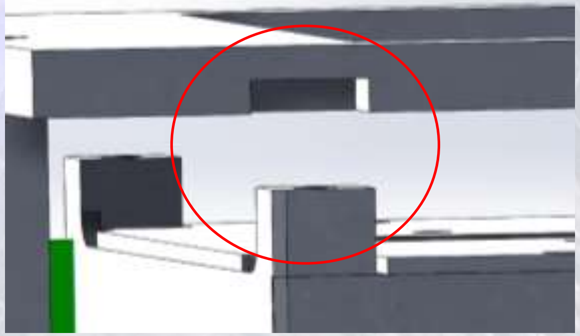
Turntable: Attachments

1. Vertical – for calibration of sensors on solar panels and belly
   - Supports 1, 2, and 3U
     - 3U length = 13.4”
   - Max height supported = 15”
   - Slide channels for adjustable height
   - Corner etchings in board for alignment
   - Feet cutouts in top plate for alignment
   - Made from ¼” thick aluminum plates
   - Held together with machine screws





Corner etchings



Feet cutouts

Turntable: Attachments

2. Horizontal – for calibration of 4 side faces
   - Supports 1, 2, and 3U
   - Plate attached to board with screws
   - CubeSat held to plate with feet clamps
   - Plate and clamp keep CubeSat aligned
   - Made from single slab of aluminum

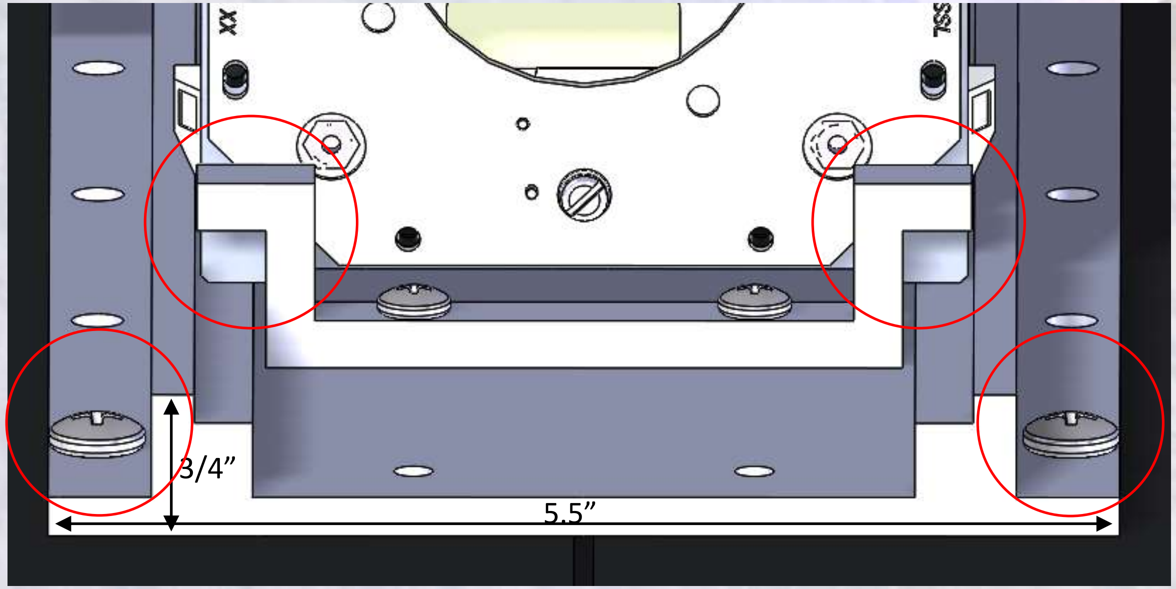
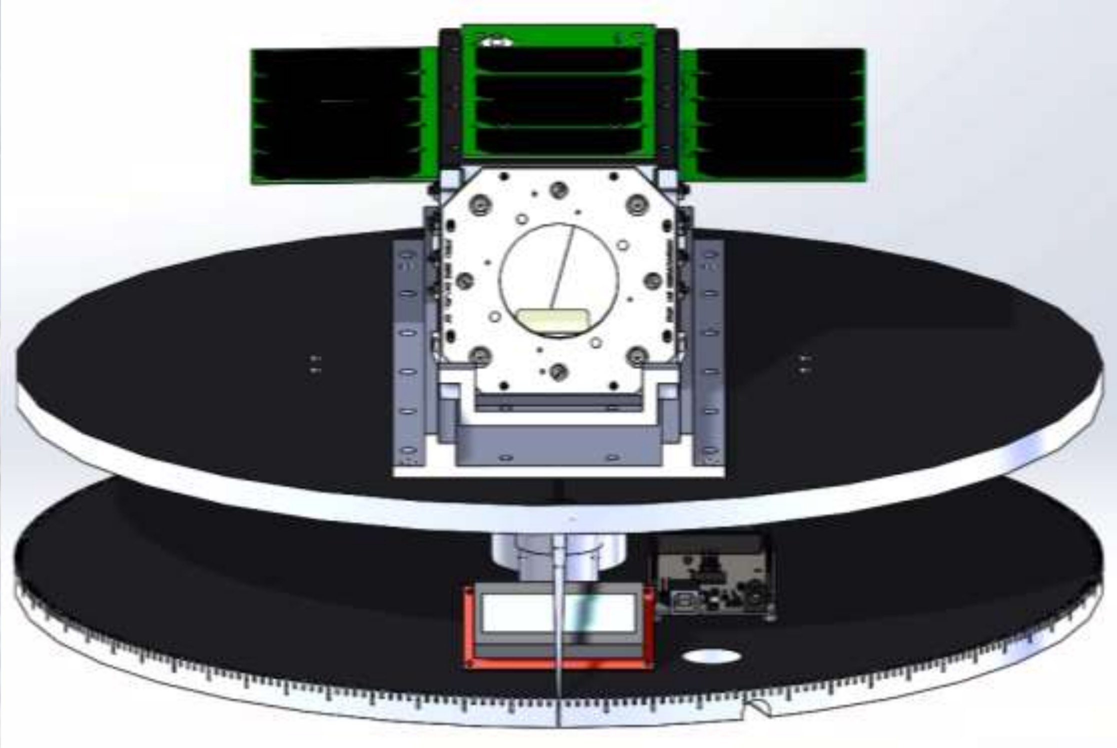
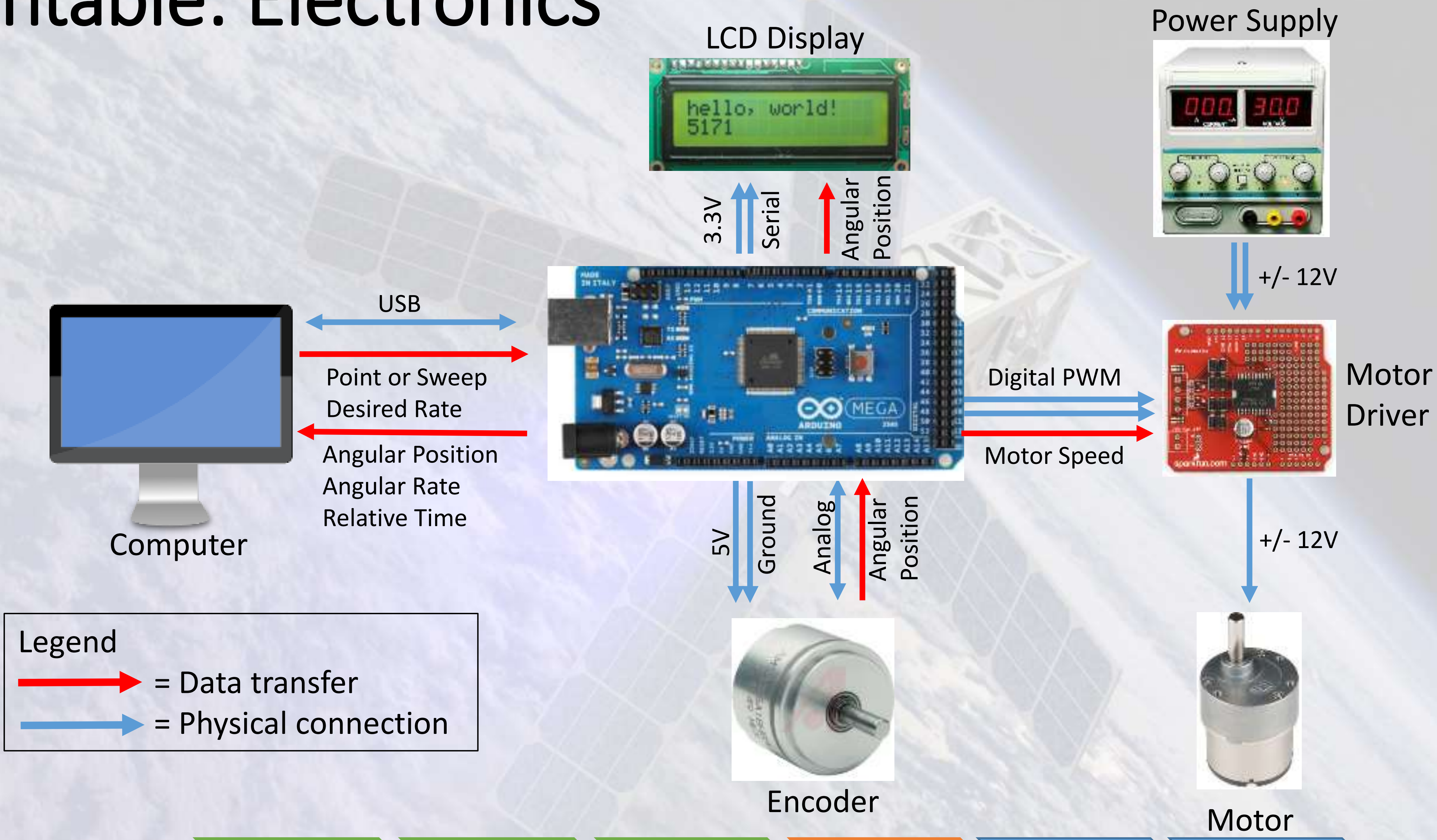


Plate attachment screws

Feet clamps

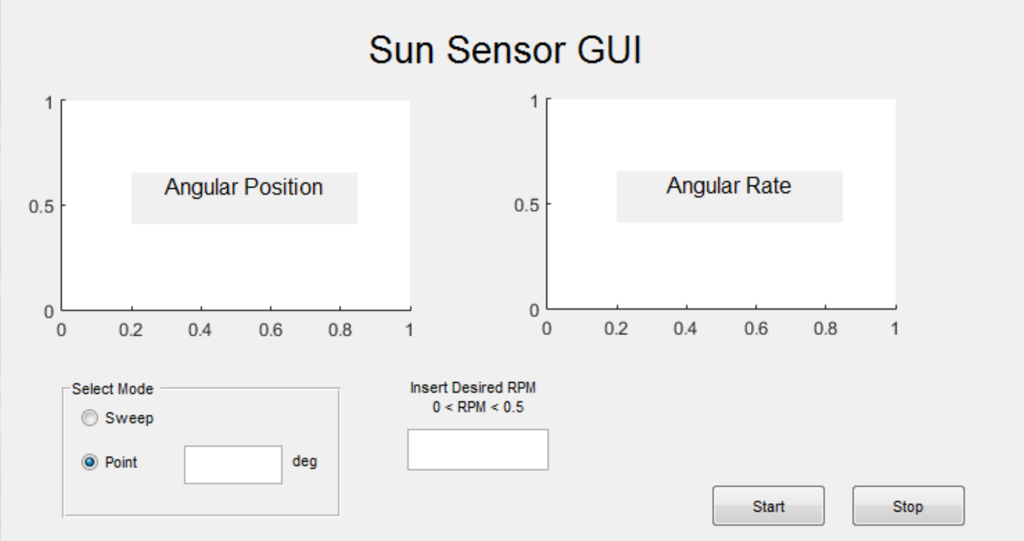


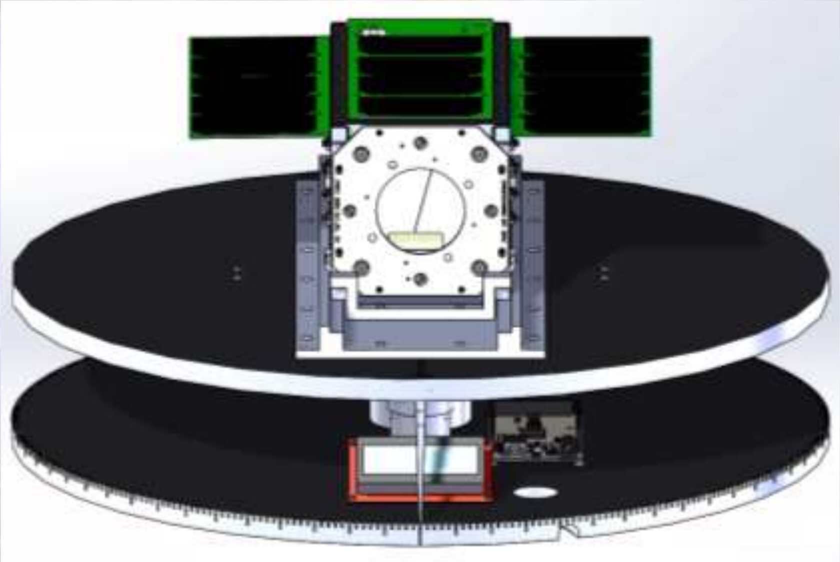
Turntable: Electronics



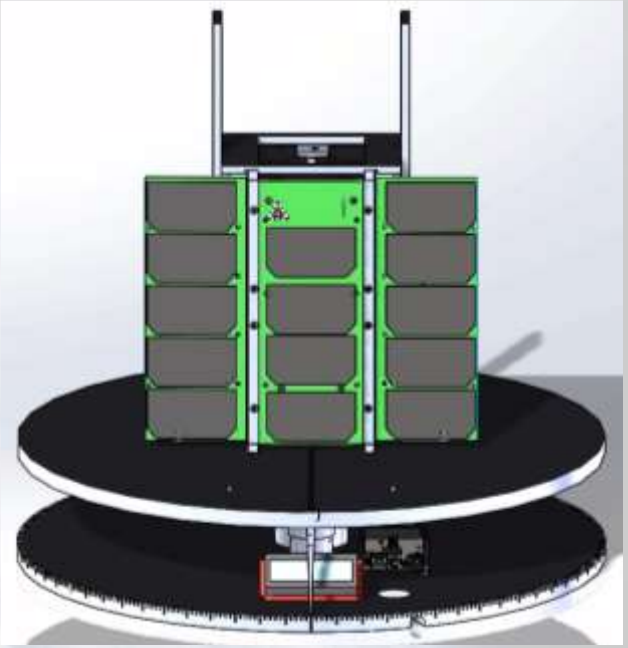
Turntable: Operation

- Table will be controlled by Matlab GUI and Arduino firmware
  - Will log angular position, angular velocity, and relative time
- Two preset rotation types
  1. Sweep – rotates to 0° then rotates through 360° at desired rate (0 to ½ RPM)
  2. Point – rotates to desired angle at desired rate





Sweep



Point

Turntable: Verification and Validation

1. Table can rotate slow enough to achieve 1 sample per degree minimum requirement
   - Time for 1 rotation ≥ 36 seconds (5/3 RPM)

     Sun sensors = 10 Hz

$$10\ Hz = \frac{10\ \cancel{samples}}{1\ second} * \frac{1\ \cancel{degree}}{1\ \cancel{sample}} * \frac{1\ rotation}{360\ \cancel{degrees}} = \frac{1\ rotation}{36\ seconds} = \frac{5}{3} RPM$$

   - Max RPM of table = ½
     - 120 seconds for 1 rotation
   - Perform test with stopwatch to confirm time to rotate is correct
2. Table can rotate to desired angle
   - Compare encoder reading to angle etchings and position calculated with angular rate and time

HelmHoltz Cage Apparatus

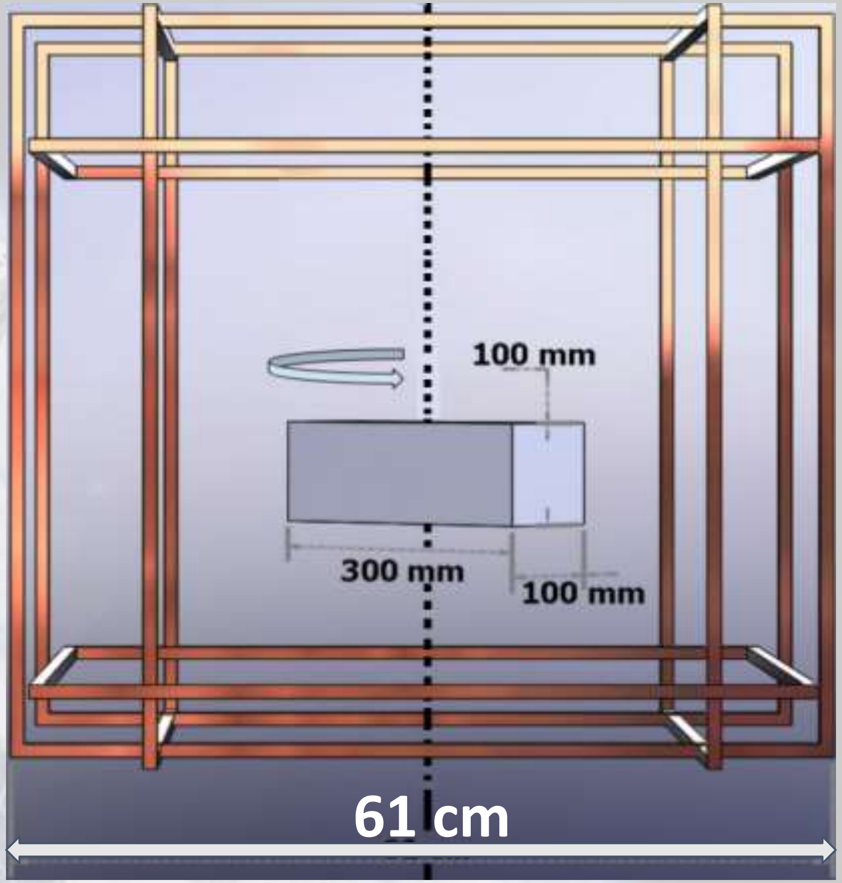
Helmholtz Cage Testing Structure: Design Requirements

TEST:

- The QB50 will sense a simulated attitude and fire its magnetorquers to correct it
    - The interface board is not connected for this test

Requirements

- Allow for the assessment of magnetorquer functionality (direction of actuation) along 1 axis
    - Do so in less than 15 minutes
- Do not interfere with the Satellite's magnetometer readings
- Ensure the safety of the satellite during testing

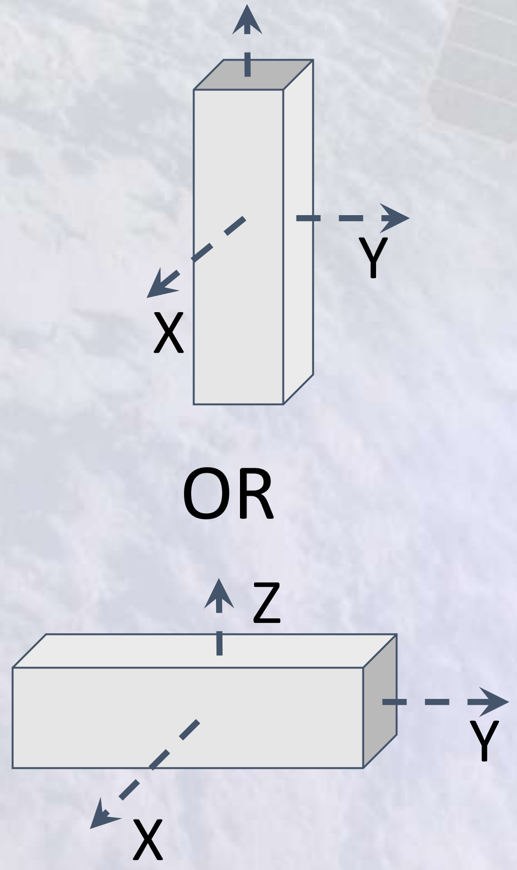


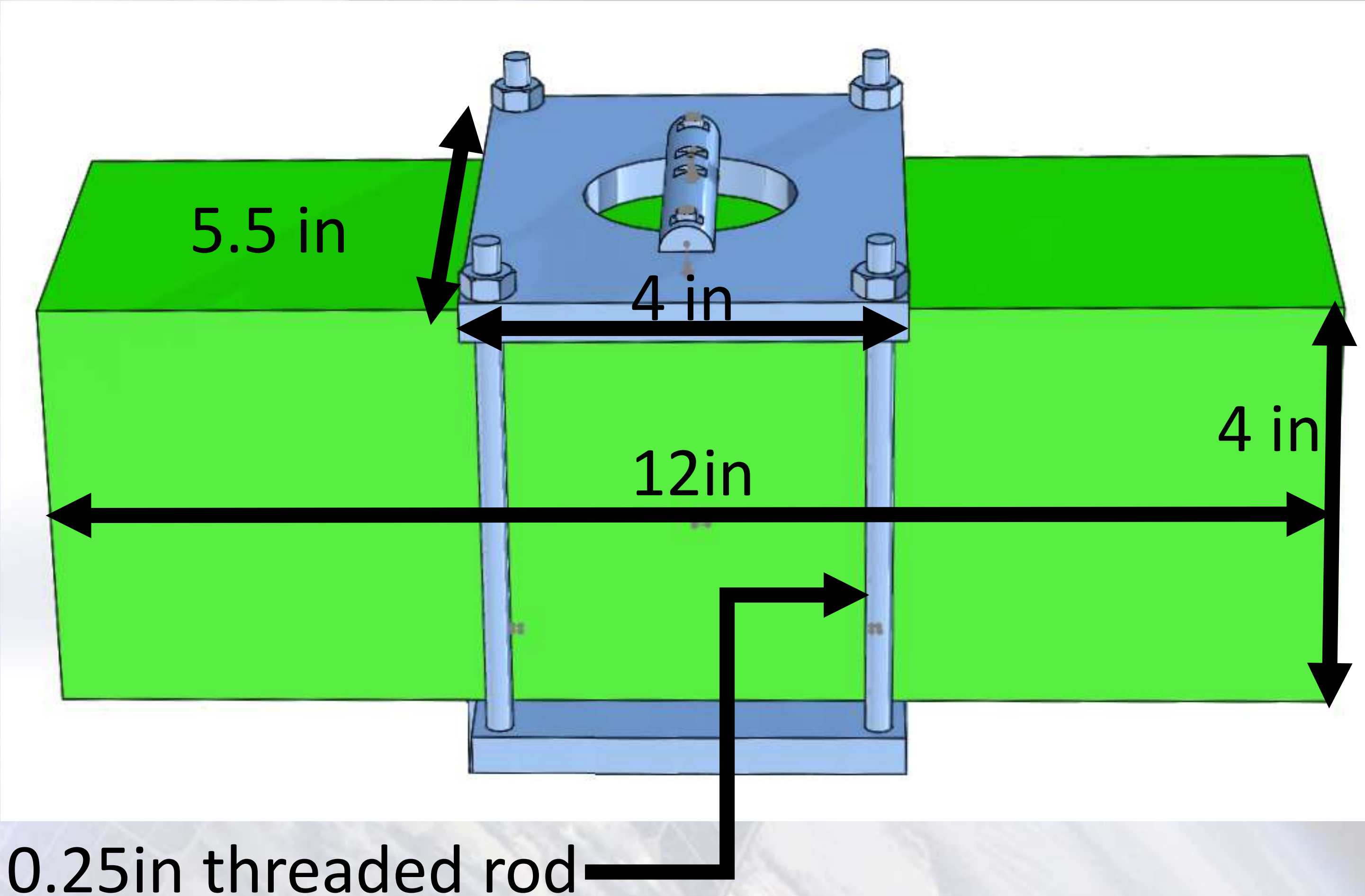
CRITICAL ELEMENT: Minimize line torque to maximize impact of magnetorquers

Helmholtz Cage Testing Structure: Baseline Design

Helmholtz Cage Testing Structure: Attachment Orientation 1

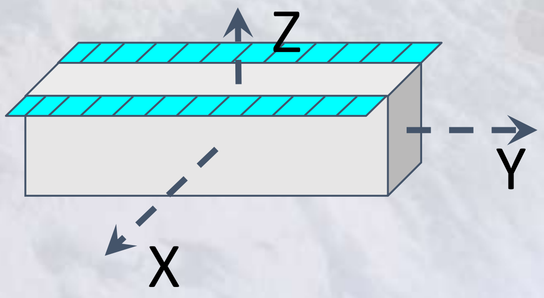
Orienation:



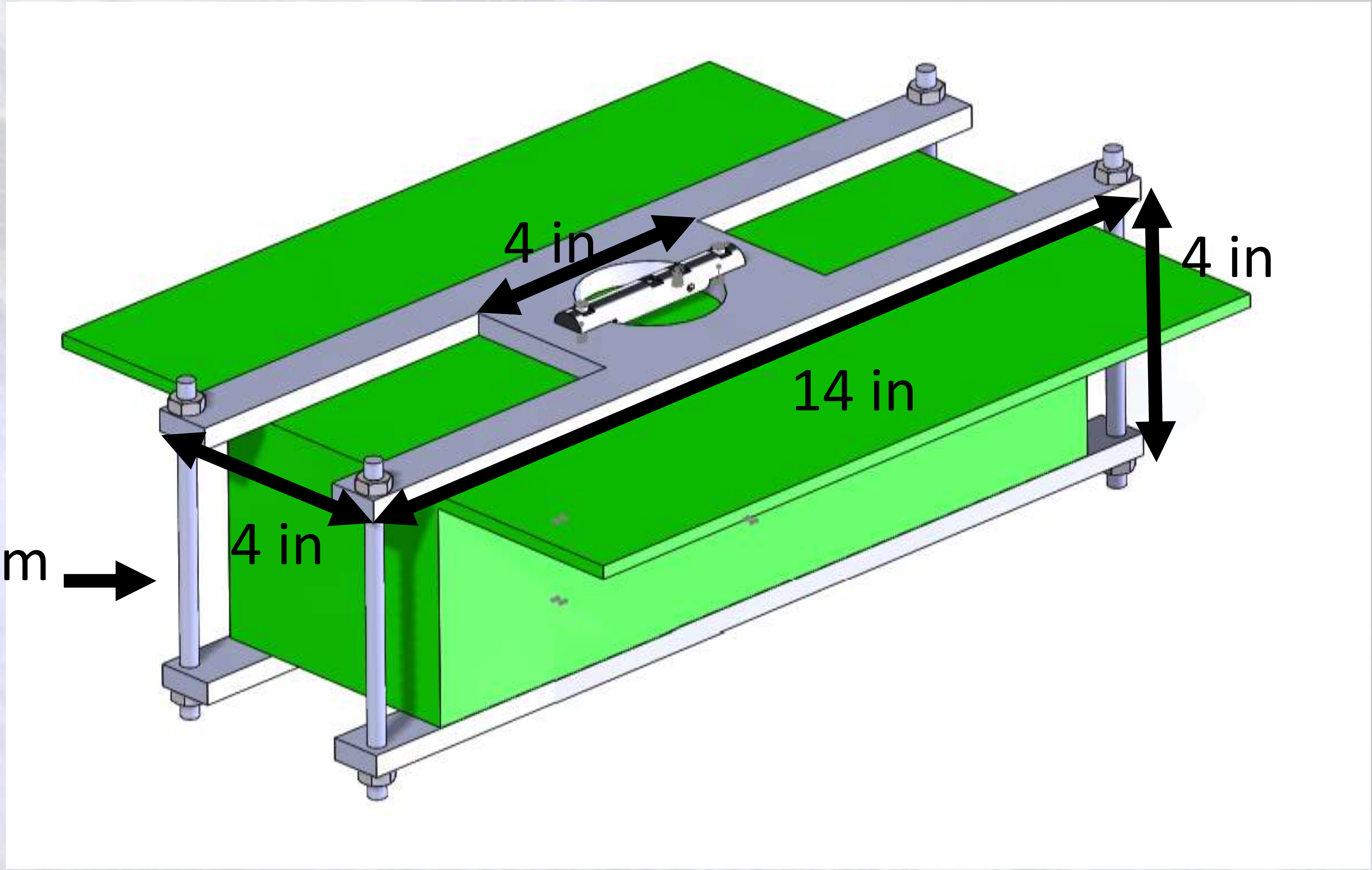


Helmholtz Cage Testing Structure: Attachment Orientation 2

Orientation:

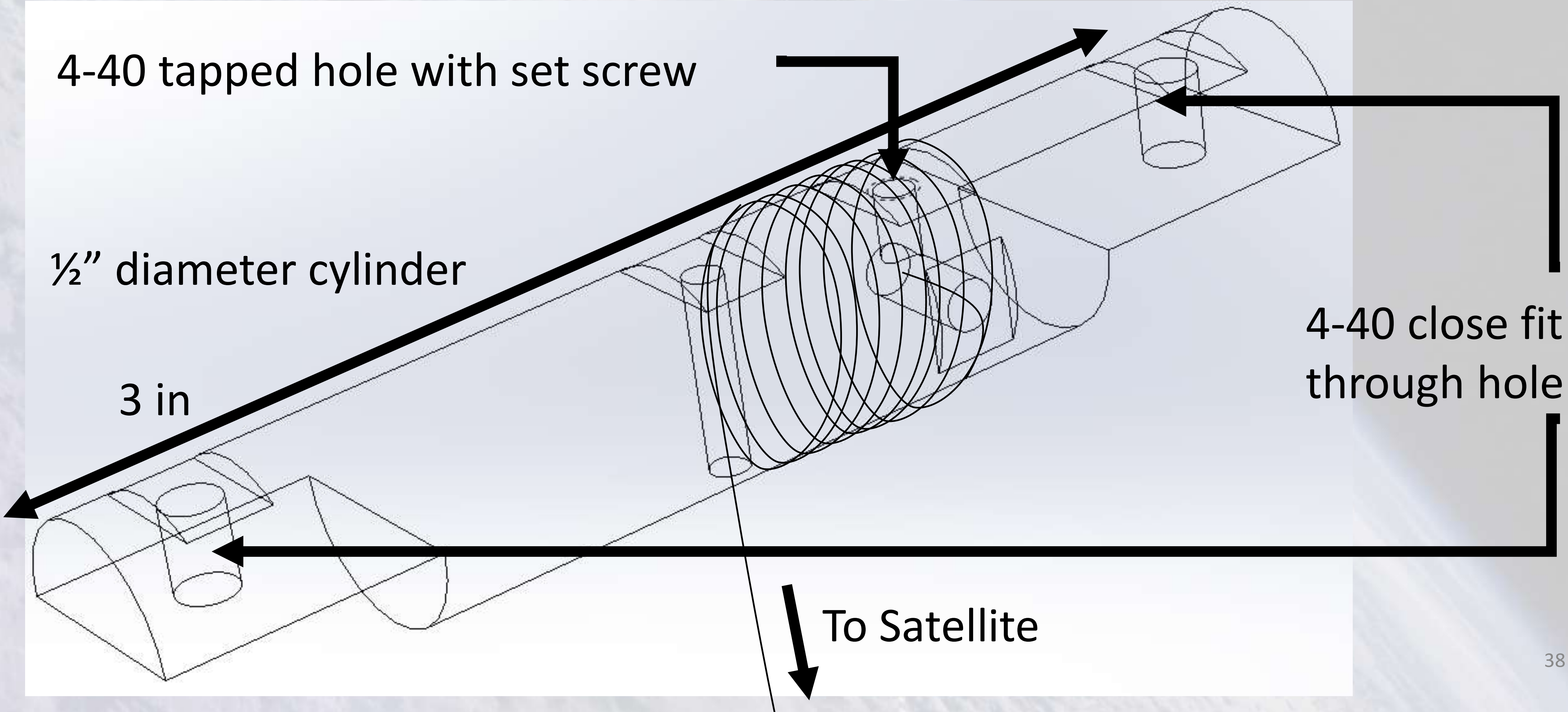


0.25 in aluminum threaded rod



Helmholtz Cage Testing Structure: Attachment

Same attachment on clamps and at top of structure



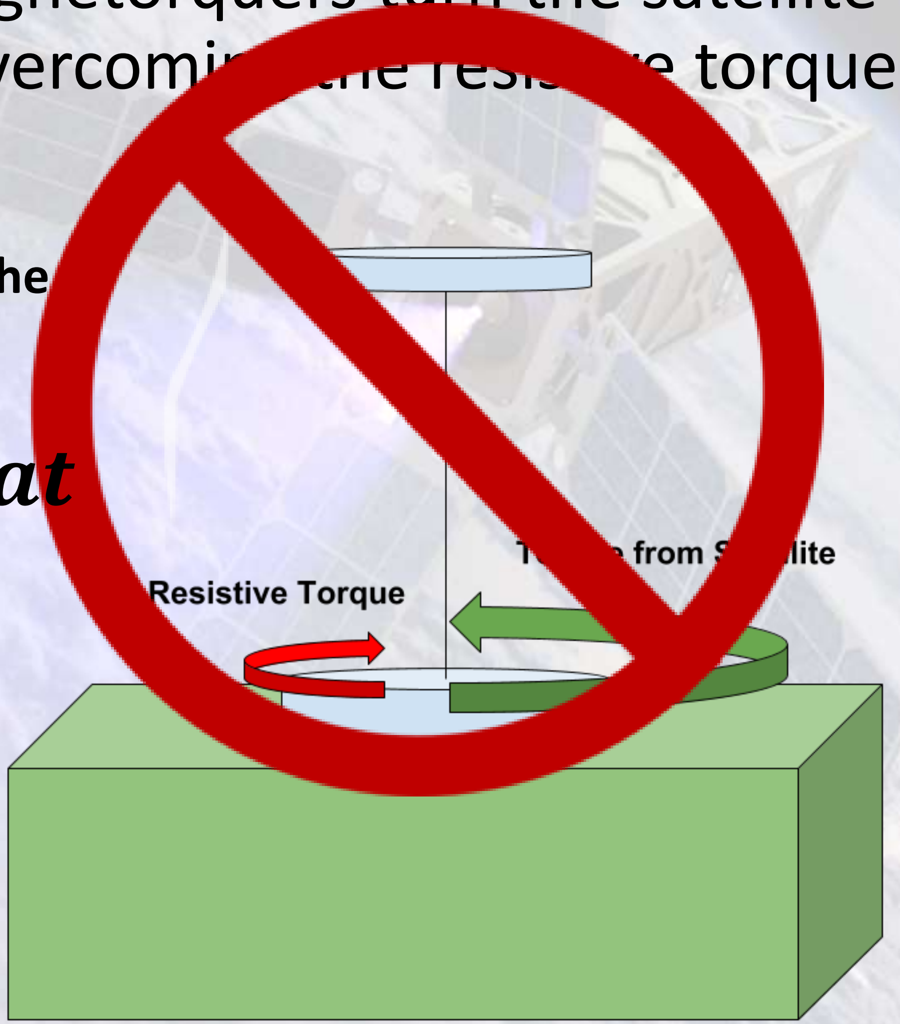
Helmholtz Cage Testing Structure: Previous Test Design

Operating Principle

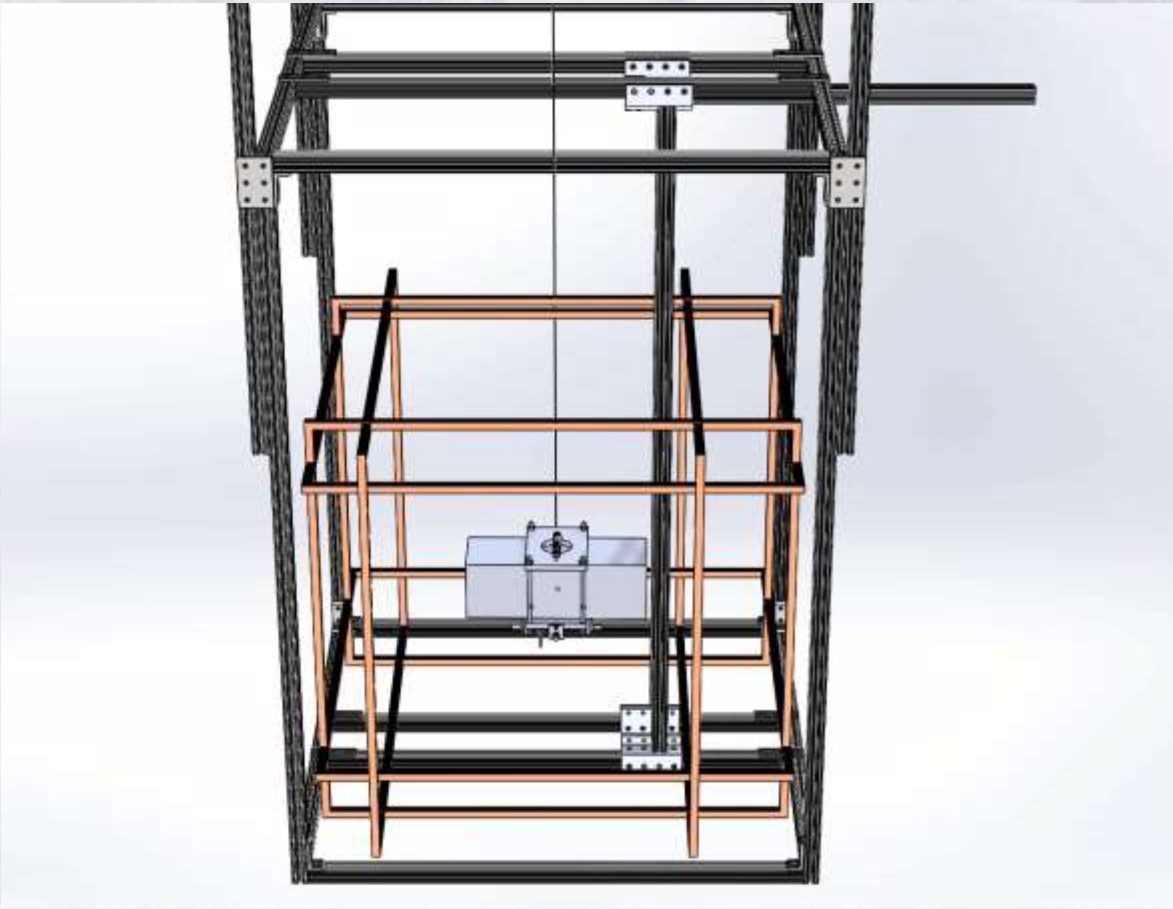
Magnetorquers turn the satellite by overcoming the resistive torque

Resistive torque is greater than the magnetorquer torque

$$\tau_{Line} > \tau_{Sat}$$



Helmholtz Cage Testing Structure: New Test Design



1. Satellite turned clockwise by hand (NO MAGNETORQUERS)
2. Measure time for satellite to rotate back to zero
3. Repeat 1 and 2 counterclockwise
4. Satellite turned clockwise by hand (MAGNETORQUERS ON)
5. Measure time for satellite to rotate back to zero
6. Repeat 4 and 5 counterclockwise

Time shown in minutes : seconds

Helmholtz Cage Testing Structure: Design - Proof of Requirement Satisfaction

Satellite can cause a significant change in the time to rotate

$$t_{tr} = \sqrt{2 * \theta * I *}$$

$$\tau_N = \tau_{Line} + \tau_{Sat}$$

t_{tr} = time to rotate

t_{tr} was found experimentally to find τ_{Line}

t_{tr} with τ_{Sat} was found using:

Test Specifications

12 trials with 4 kg mass model

7 ft suspension line

θ = 360 degrees

Moment of Inertia calculated with 5.6 kg mass

τ	t_{tr}	Δt_{tr}
τ_{Line}	2.75 minutes ± 7.5 seconds	0
$\tau_{Line} + \tau_{Sat}$	2.25 minutes	-30 seconds
$\tau_{Line} - \tau_{Sat}$	3.5 minutes	+45 seconds

Green = Found Experimentally

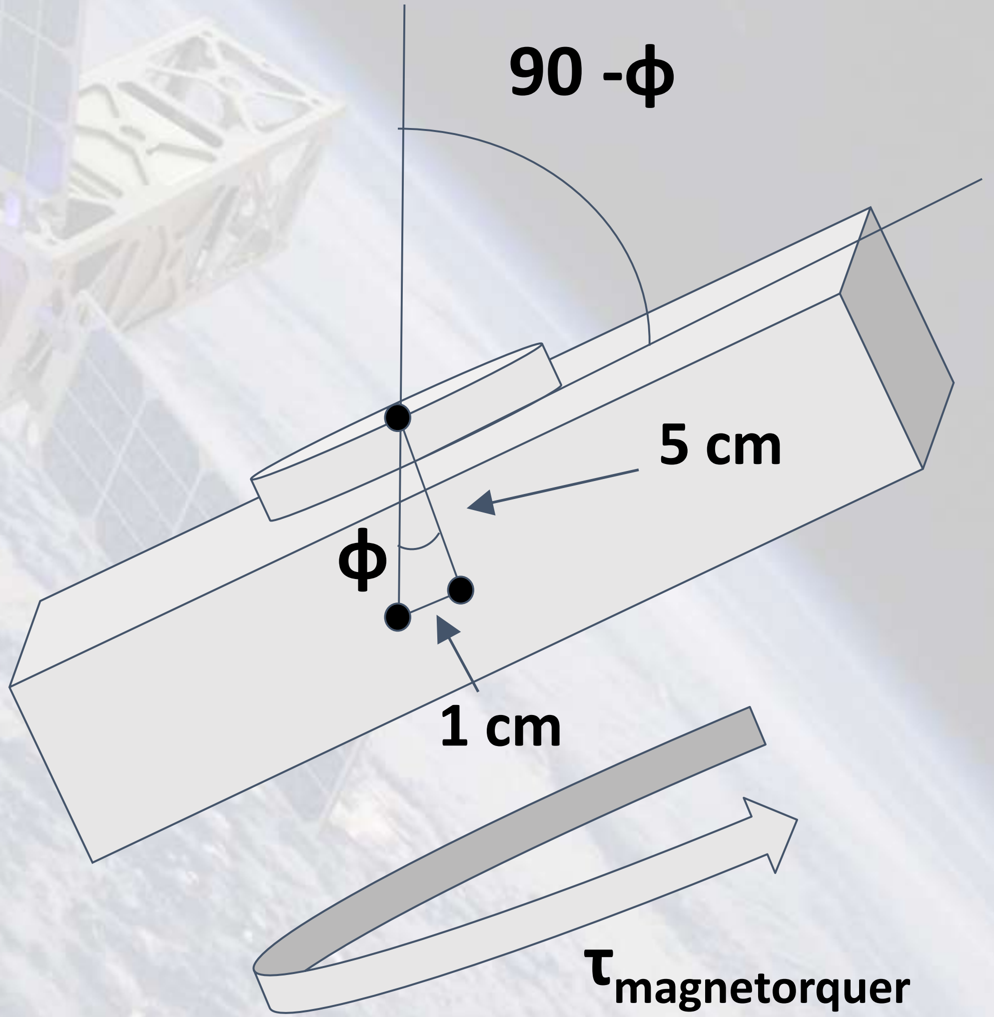
Blue = Found Analytically

Helmholtz Cage Testing Structure: Backup Calculations - Tilting Impact

$$\tau_{sat} = \tau_{magnetorquer} * cos(\phi) = 4.9E^{-6}Nm$$

$$\tau_{Geometric\ loss} = 0.1E^{-6}Nm$$

$$\phi = tan^{-1}\left(\frac{1}{5}\right) = 11.3^{o}$$



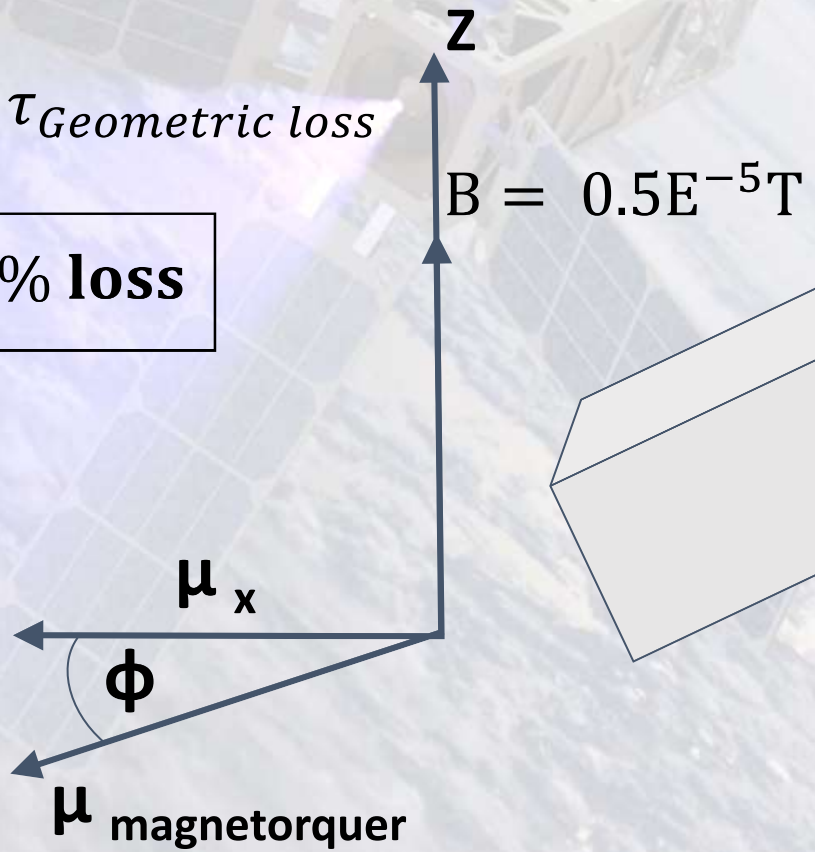
Helmholtz Cage Testing Structure: Backup Calculations - Tilting Impact

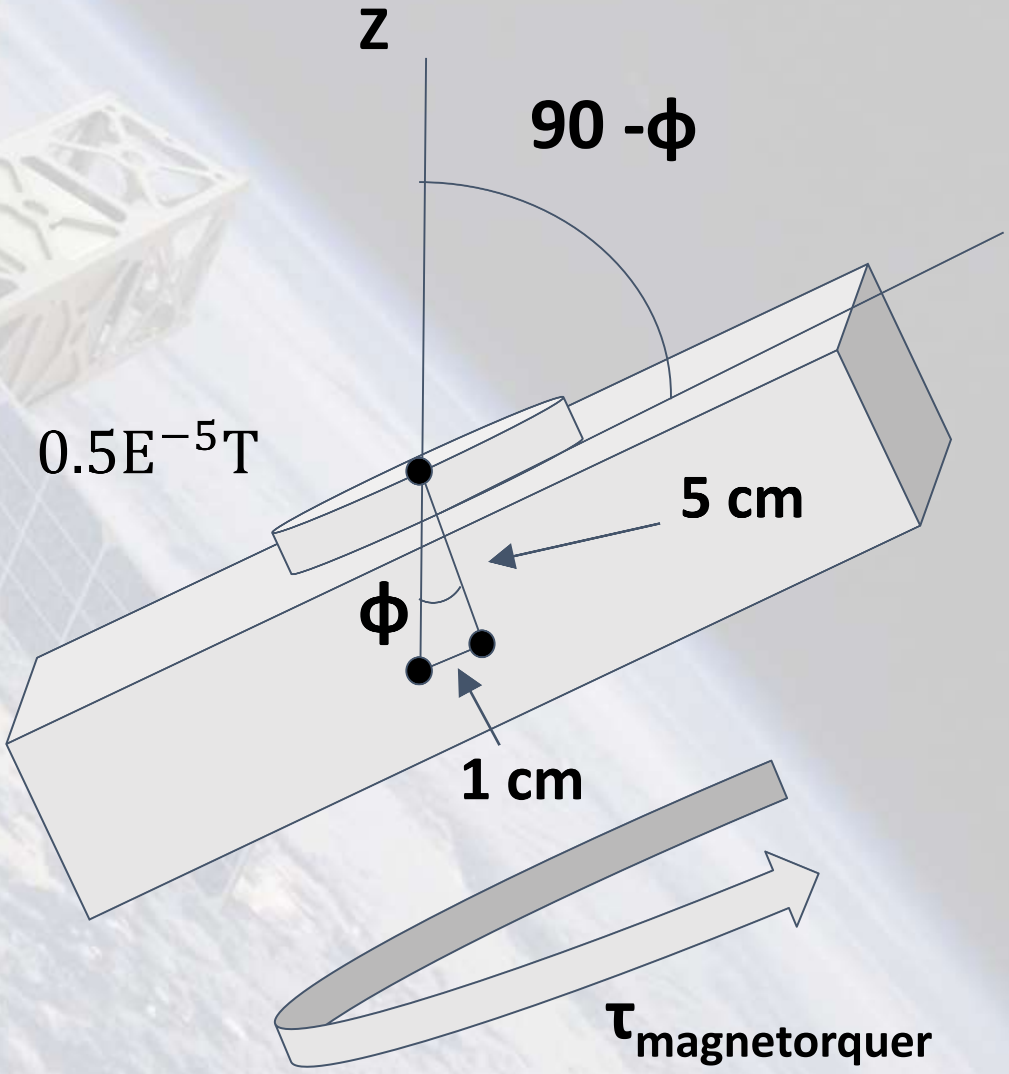
$\tau = \mu \times B = 4.9E^{-6} Nm$

$\tau_{Magnetic\ loss} = 0.1E^{-6} Nm$

$\tau_{Tilting\ loss} = \tau_{Magnetic\ loss} + \tau_{Geometric\ loss}$

$\boldsymbol{\tau_{Tilting\ loss} = 0.2E^{-6} Nm \Rightarrow 4\%\ loss}$





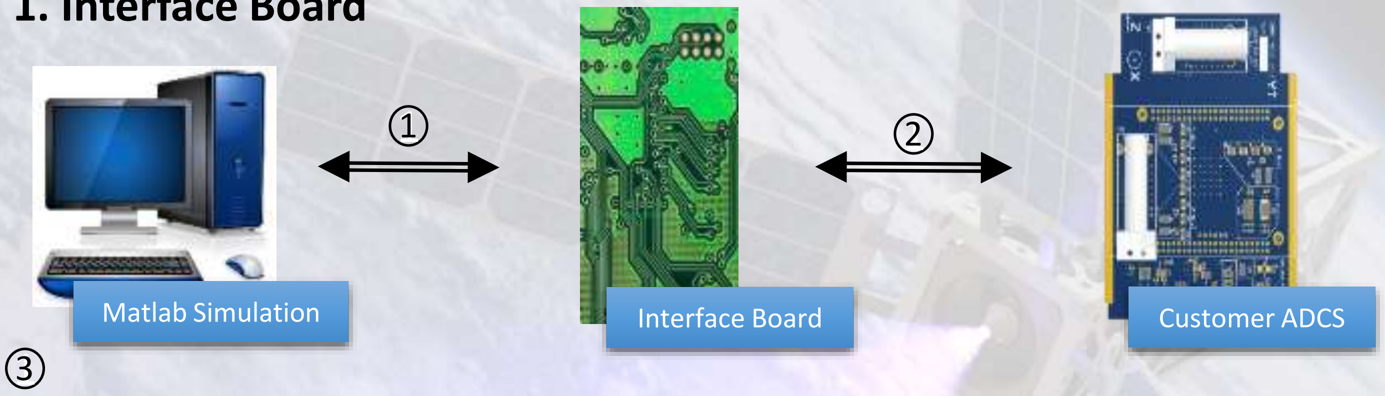
Helmholtz Cage Testing Structure: Testing

- Perform a test without magnetorquers to prove that the rotation rate is close to expected
- Repeat test to prove release mechanism is consistent
- Perform a tensile test with the attachment hardware to see when breaking or slipping occurs
- Perform a test with active magnetorquers using a magnetorquer and controller provided by the customer

Status Summary

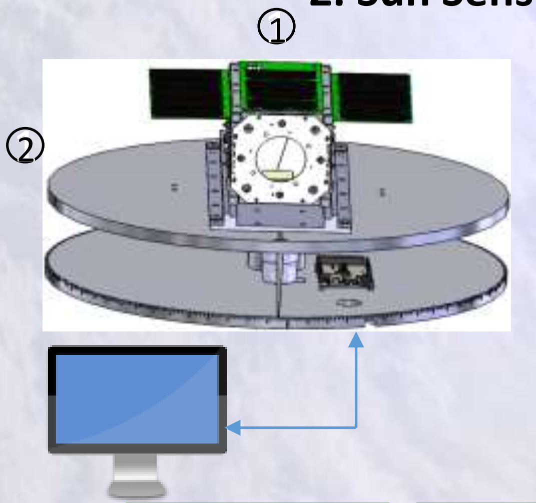
- 3 **<u>individual</u>** tests, listed in priority

1. Interface Board



1. Connect simulation to interface board
2. Connect interface board to ADCS
3. Run Simulation and log data

2. Sun Sensor Turntable



1. Integrate CubeSat
2. Rotate turntable
3. Compare table angle to angle reported by CubeSat

③

3. HelmHoltz Cage test

1. Integrate CubeSat
2. Rotate CubeSat
3. Verify functionality of magnetorquer

Risk Level Analysis

Severity → / ***Likelihood ↓***	***1***	***2***	***3***	***4***	***5***
5					
4					
3					
2					
1					

#	Likelihood
5	Very likely to occur
4	Likely to occur
3	Somewhat likely to occur
2	Unlikely to occur
1	Extremely unlikely to occur

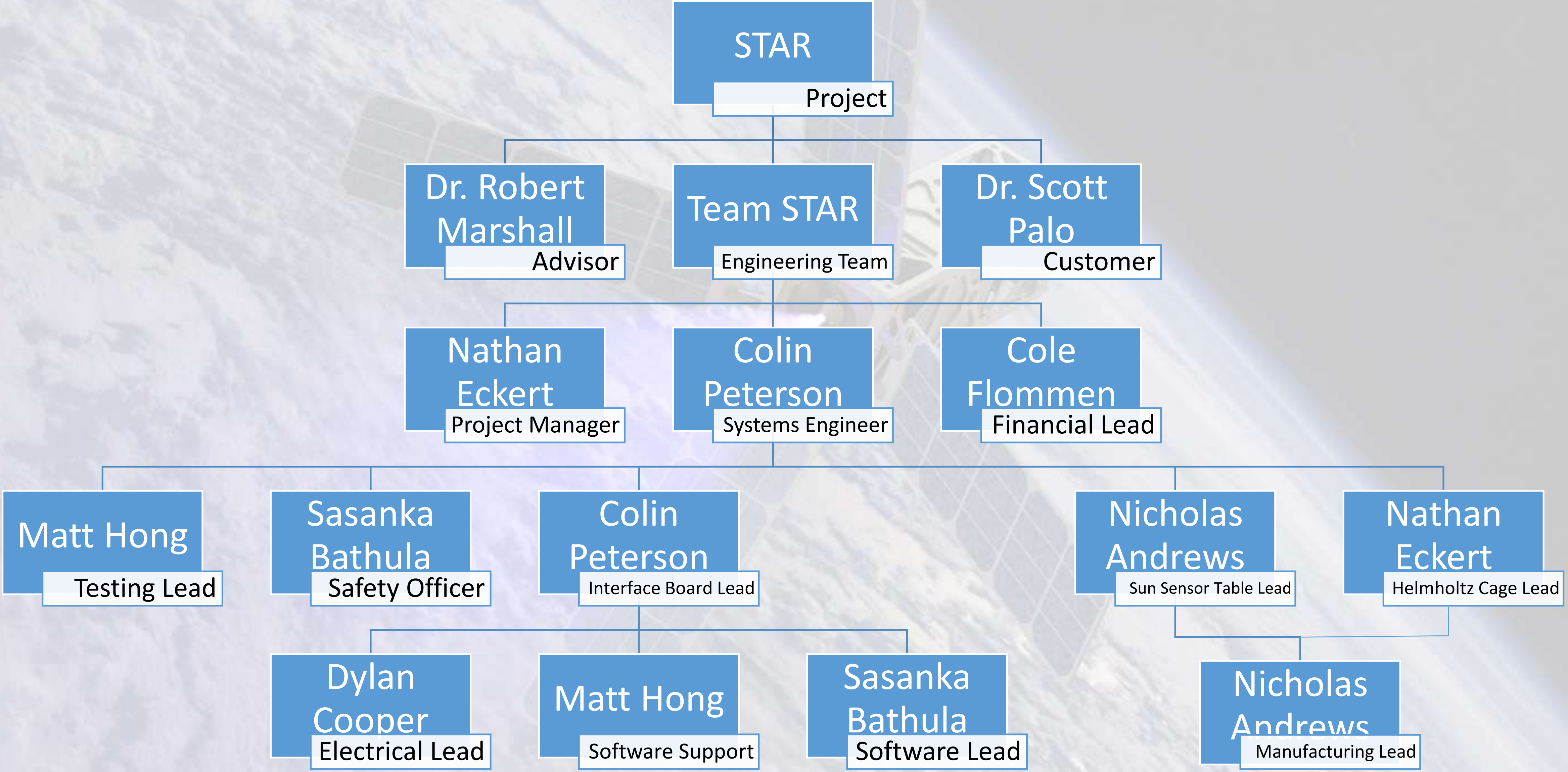
Risk Assessment

Severity → / Likelihood ↓	1	2	3	4	5
5					
4					
3	C*		C, D*	D	
2		G	A*	A	B, F
1	G*		E*	E	B*, F*

A – Original Risk   A* - Mitigated Risk

#	Risk	Mitigation
A	QB50 Sensor model not available	Development of basic sim to pass constant data to board
B	Interface board not ready	Schedule to finish early with margin
C	Matlab FTDI driver failure	Create virtual serial port object on USB using DAQ toolbox
D	Lead time for low reflectance coating	Machine coated parts first
E	EM interference between electronics	Top aluminum board will prevent disturbances
F	HH Cage line snaps	Use line with significant safety factor (2)
G	Air gust disrupts HH test	Plexiglas surrounds Helmholtz Cage

Team Organization



Work Breakdown Structure

- Project Star
  - Interface Board
    - Hardware
      - Schematic Development/FBD
      - Component and Testing Research
      - Timing Diagram
      - Cost Plan and Risk Analysis
      - ICD
      - Acquire Necessary Components
      - Assemble Test Board
      - Integrate with Software
      - Final Board Assembly
      - Test/Verify Functionality
    - Software
      - Simulation Development
      - Plan Simulation Modifications
      - Develop GUI Architecture
      - ICD
      - Risk Analysis
      - Verify Simulation Functionality and Results
      - Validate Sensor Models/Update Models
      - Test Program for Simulation-IB Datalink
      - Full Simulation Model Implementation
  - Hanging/Helmholtz Cage Test
    - Solidworks Model
    - Line Testing
    - Itemized List/Cost Plan
    - Research Material Acquisition
    - Risk Analysis
    - Acquire/Machine Required Materials
    - Final Assembly
    - Test/Verify Functionality
  - Sun Sensor Calibration Table
    - Solidworks Model
    - Research Material Acquisition
    - Examine Graduate Team Hardware
    - Electronics Schematics/Flowchart
    - ICD
    - Itemized List/Cost Plan
    - Risk Analysis
    - Acquire/Machine Required Materials
    - Component Finishing/Anodizing
    - Electronic Integration
    - Final Assembly
    - Test/Verify Functionality
  - Administration
    - Budget Control/Cost Plans
    - Scheduling/Timeline Development
    - Project Notebooks
    - Meeting/Lab Room Reservations
    - Project Deliverables

COMPLETED

TO BE COMPLETED

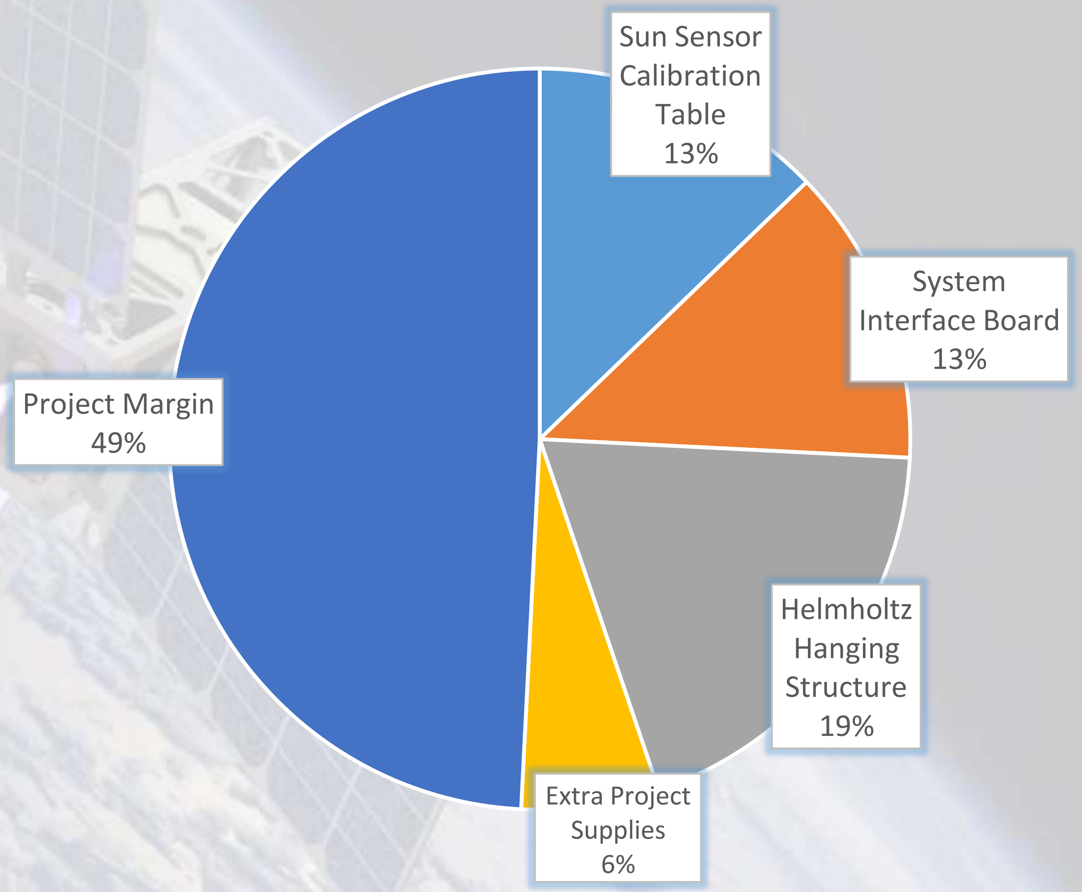
CONTINUOUS

Full Cost Plan

- Project Funding: $5,000

- Project Cost at CDR: $2,540
  - Helmholtz structure: slot mounts and extruded aluminum
  - Sun Sensor Table: anodizing coating
  - Interface Board: 4 layer PCB

- Project Margin at CDR: $2,460
  - ~50%



Mission Introduction | Project Description | Interface Board | Sun Sensor Table | Helmholtz Cage Test | Status Summary

HH Cage/SS Table Timeline

Completed
To Be Completed
Continuous
Milestones

Project STAR Gantt Chart – Hanging Helmholtz Cage

	Start Date	Finish Date
Hanging Helmholtz Cage Structure	**10/1/2015**	**4/25/2015**
Solidworks Model	10/1/2015	11/30/2015
Line Testing	10/26/2015	11/10/2015
Research Material Acquisition	11/1/2015	11/20/2015
Itemized List/Cost Plan	11/8/2015	11/20/2015
Risk Analysis	11/15/2015	11/30/2015
Acquire/Machine Required Materials	1/11/2016	3/4/2016
Final Assembly	2/26/2016	3/11/2016
Test/Verify Functionality	3/11/2016	4/25/2016

Project STAR Gantt Chart – Sun Sensor Calibration Table

	Start Date	Finish Date
Sun Sensor Calibration Table	**10/1/2015**	**4/25/2016**
Solidworks Model	10/1/2015	11/30/2015
Research Material Acquisition	10/8/2015	11/20/2015
ICD	10/15/2015	11/30/2015
Examine Graduate Team Hardware	11/1/2015	11/20/2015
Electronics Schematics/Flowchart	11/1/2015	11/30/2015
Itemized List/Cost Plan	11/1/2015	11/30/2015
Risk Analysis	11/15/2015	11/30/2015
Acquire/Machine Required Materials	12/15/2015	3/15/2016
Component Finishing/Anodizing	2/12/2016	3/15/2016
Electronic Integration	3/1/2016	3/20/2016
Final Assembly	3/15/2016	3/30/2016
Test/Verify Functionality	3/21/2016	4/25/2016

Interface Board/Administration Timeline

Completed
To Be Completed
Continuous
Milestones

Project STAR Gantt Chart – Interface Board

August, September, October, November, December, January, Februaru, March, April, May

	Start Date	Finish Date
Interface Board		
Hardware	**9/16/2016**	**4/25/2016**
Schematic Development/FBD	9/16/2015	11/20/2015
Component and Testing Research	10/8/2015	11/8/2015
Timing Diagram	10/8/2015	11/6/2015
Cost Plan and Risk Analysis	10/21/2015	11/20/2015
ICD	10/15/2015	11/30/2015
Acquire Necessary Components	12/16/2015	2/29/2016
Assemble Test Board	1/22/2016	2/16/2016
Integrate with Software	2/8/2016	3/1/2016
Final Board Assembly	2/22/2016	3/22/2016
Test/Verify Functionality	3/16/2016	4/25/2016
Software	**9/15/2015**	**4/25/2015**
Develop GUI Architecture	9/15/2015	11/6/2015
Simulation Development	10/1/2015	1/11/2015
ICD	10/15/2015	11/30/2015
Plan Simulation Modifications	11/1/2015	1/11/2015
Risk Analysis	11/15/2015	11/30/2015
Verify Simulation Functionality and Results	1/11/2016	2/11/2016
Validate Sensor Models/Update Models	2/12/2016	3/12/2016
Test Program for Simulation-IB Datalink	3/13/2016	3/31/2016
Full Simulation Model Implementation	4/1/2016	4/25/2016

Project STAR Gantt Chart - Administration

August, September, October, November, December, January, Februaru, March, April, May

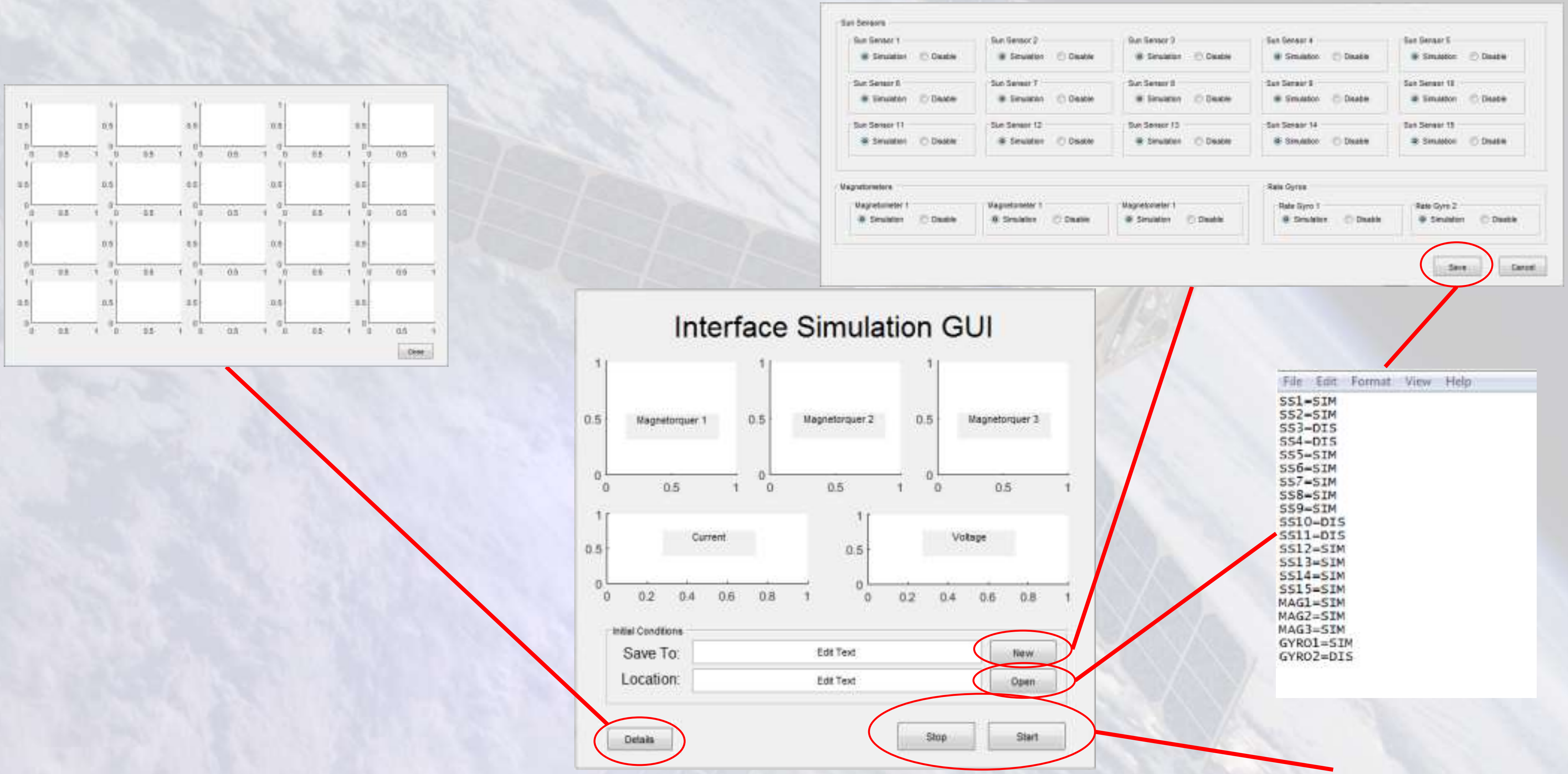
	Start Date	Finish Date
Administration	**8/24/2015**	**4/25/2016**
Project Notebooks	8/24/2015	4/25/2016
Meeting/Lab Room Reservations	9/1/2015	4/25/2016
Budget Control/Cost Plans	9/15/2015	4/25/2016
Scheduling/Timeline Development	9/21/2015	4/25/2016
Project Deliverables		

Milestones: PDD, CDD, PDR, CDR, FFR

Questions?

Backup Slides

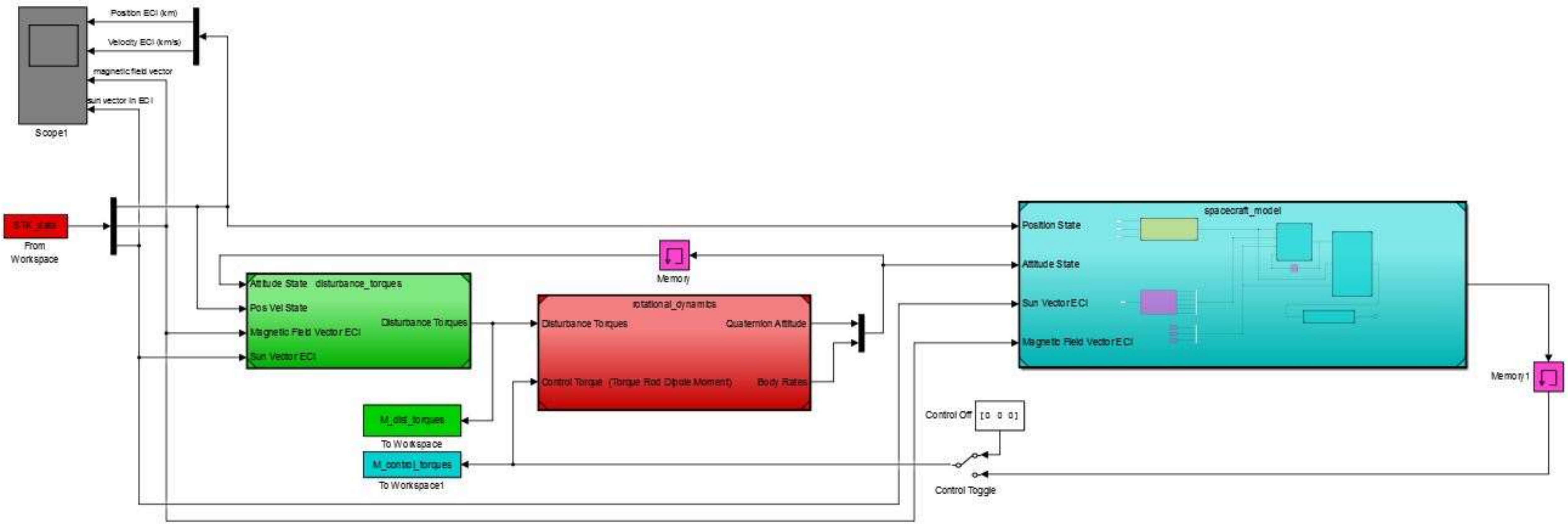
Interface Board GUI



Start and Stop Simulation

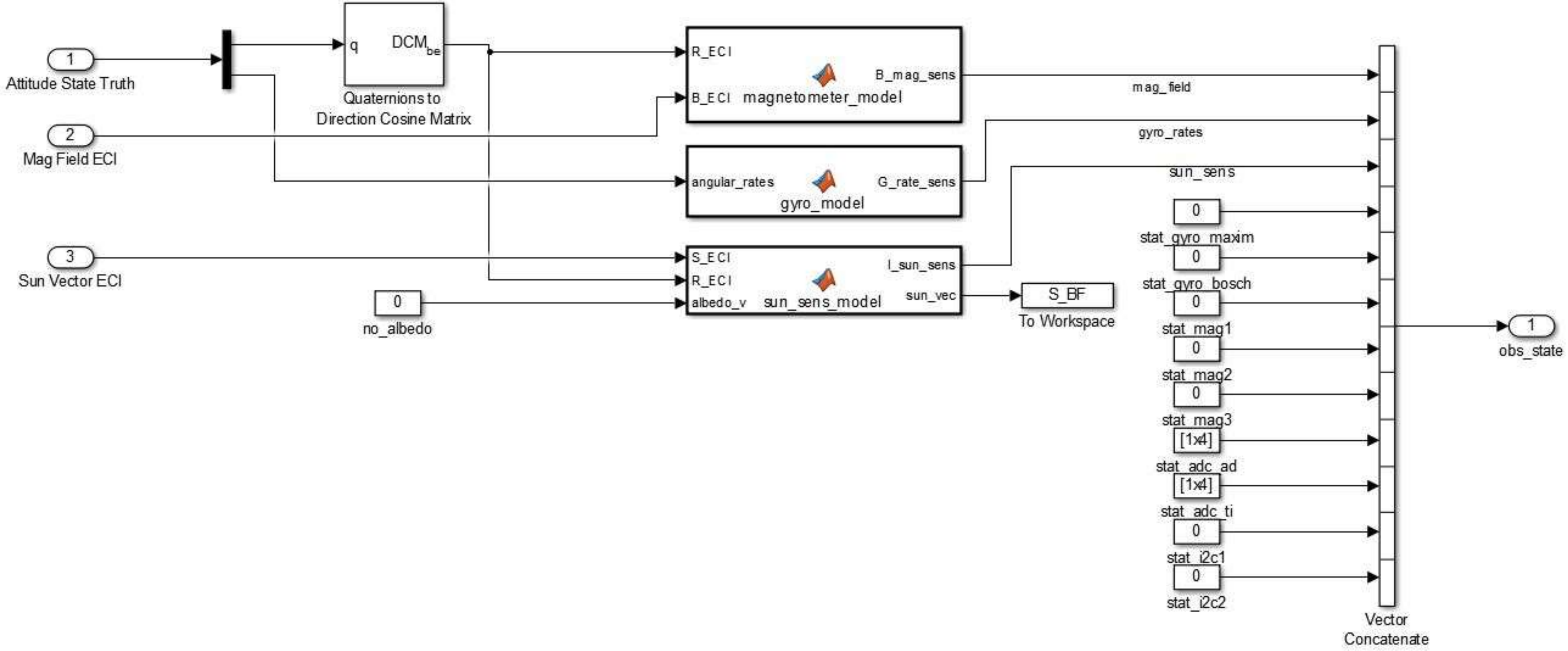
(Backup)

CUBESAT SIMULATION MODEL



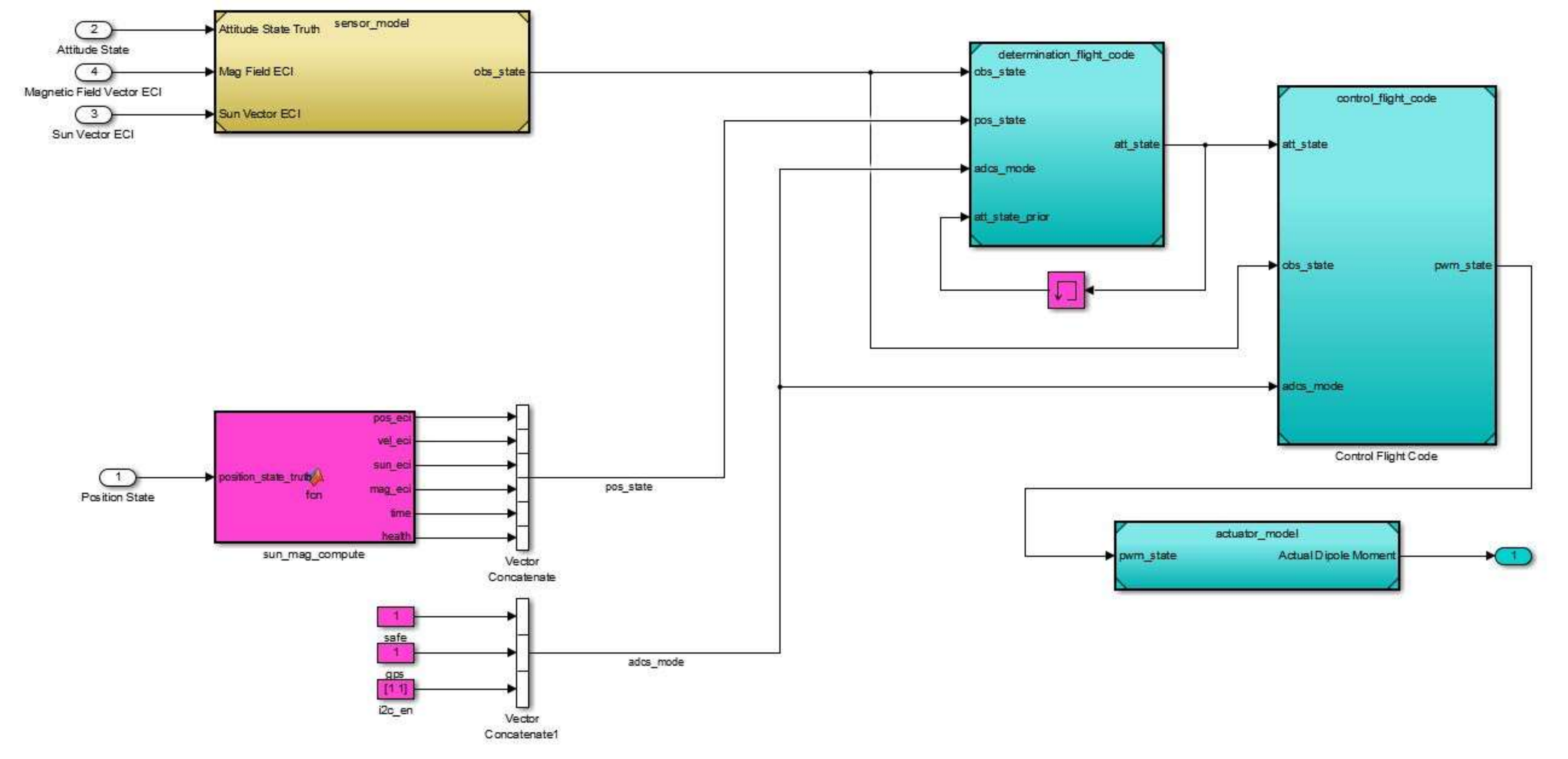
(Backup)

CUBESAT SIMULATION MODEL

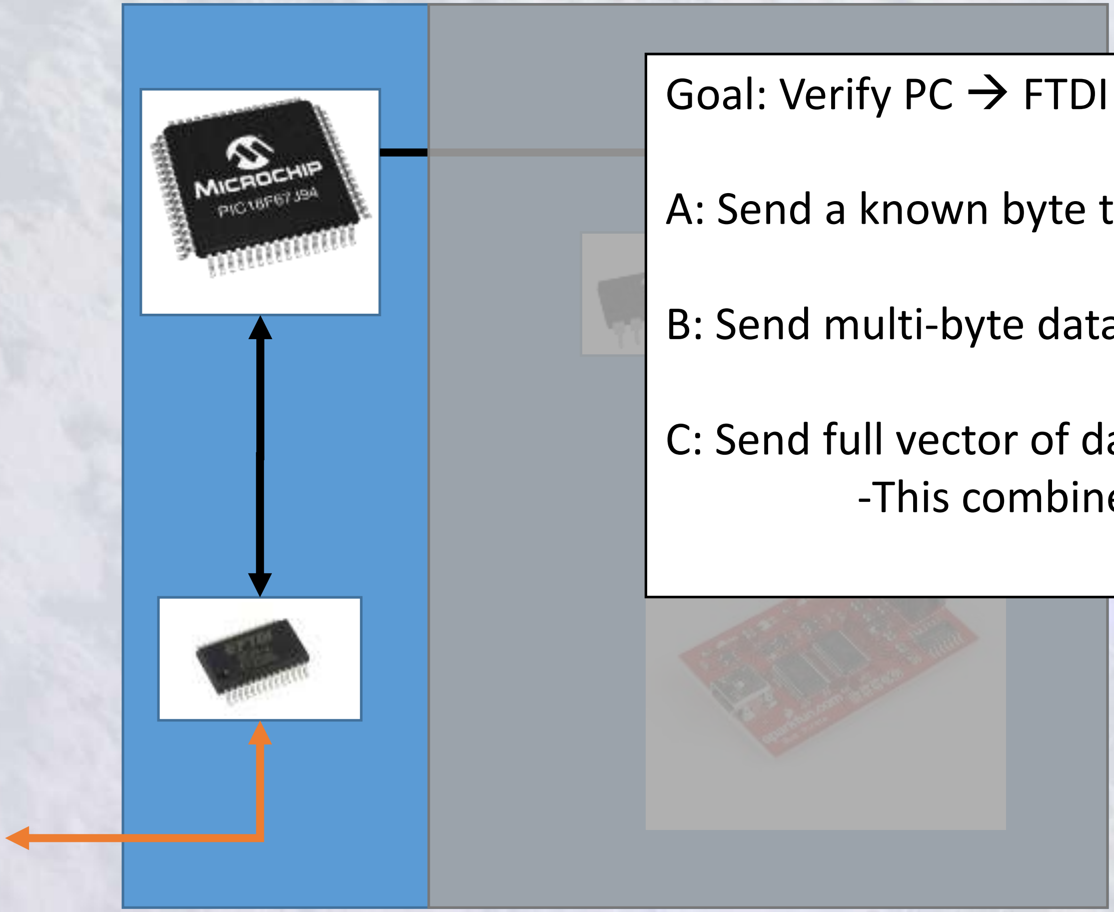


(Backup)

CUBESAT SIMULATION MODEL



Testing Board Verification – Step 1



Goal: Verify PC → FTDI Chip → MμC

A: Send a known byte through Matlab, display on MμC LCD

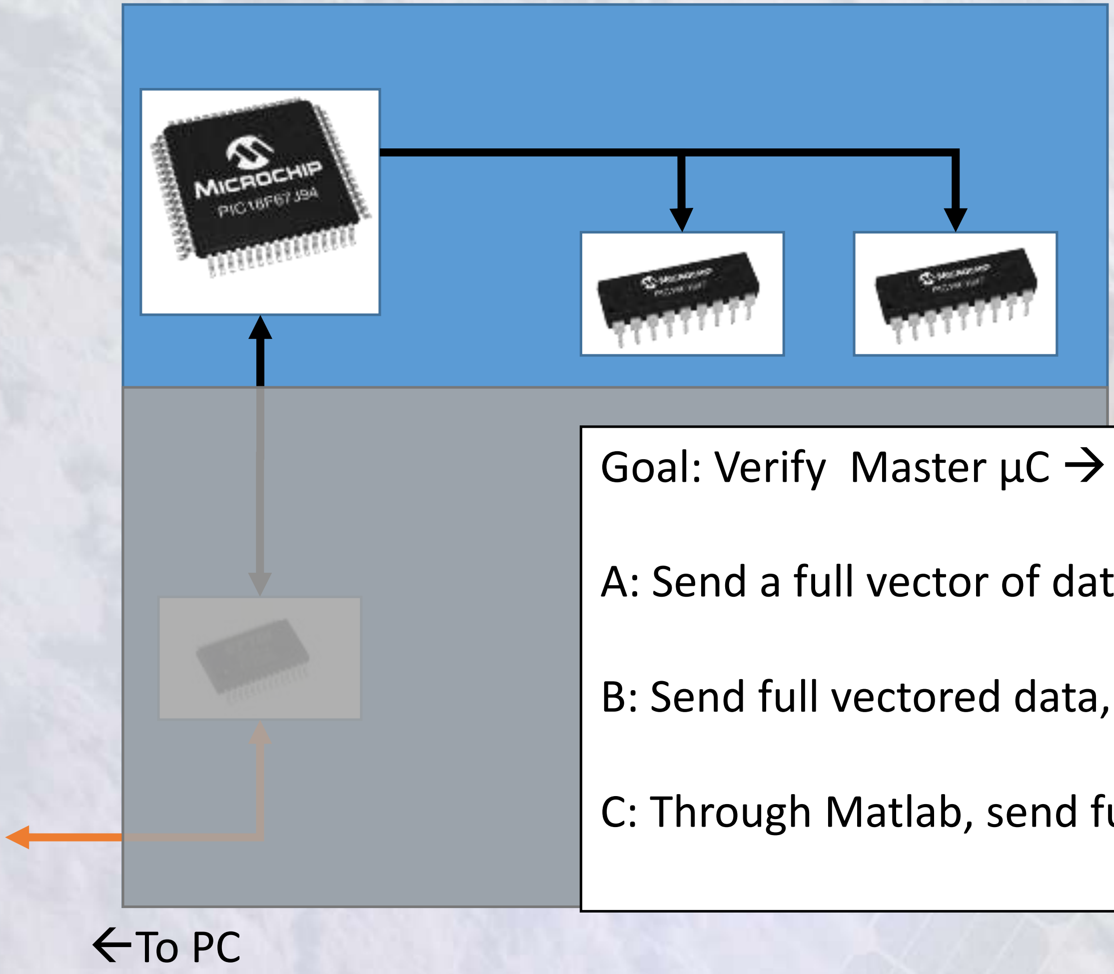
B: Send multi-byte data i.e. floating point, display on MμC LCD

C: Send full vector of data, display data points on LCD
-This combines the LCD with a timer to flip through the various data points

←To PC

*Design not to scale

Testing Board Verification – Step 2



Goal: Verify Master µC → Slave µC

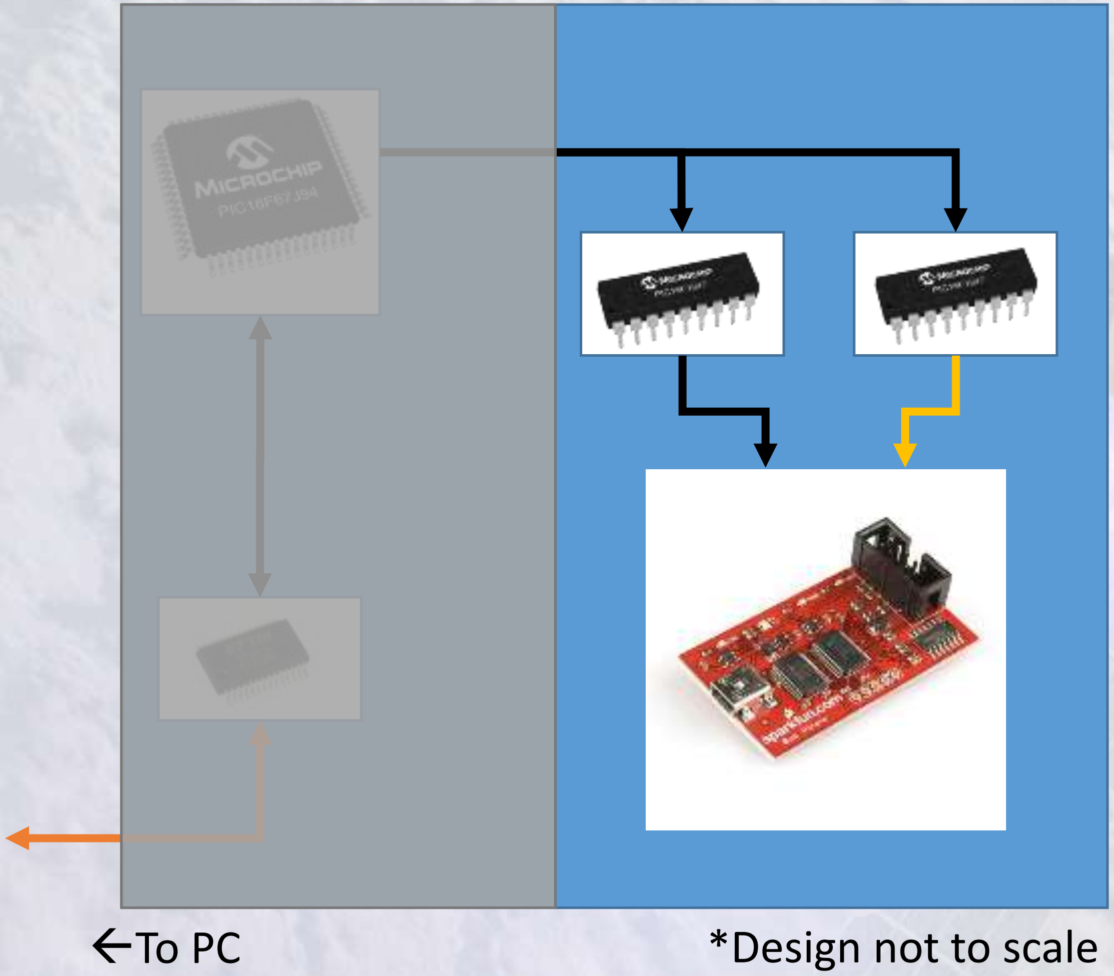
A: Send a full vector of data, flash an LED on Slave µC when it receives its data

B: Send full vectored data, show byte on Slave µC's LCD

C: Through Matlab, send full data vector, verify with Logic Analyzer

*Design not to scale

Testing Board Verification – Step 3

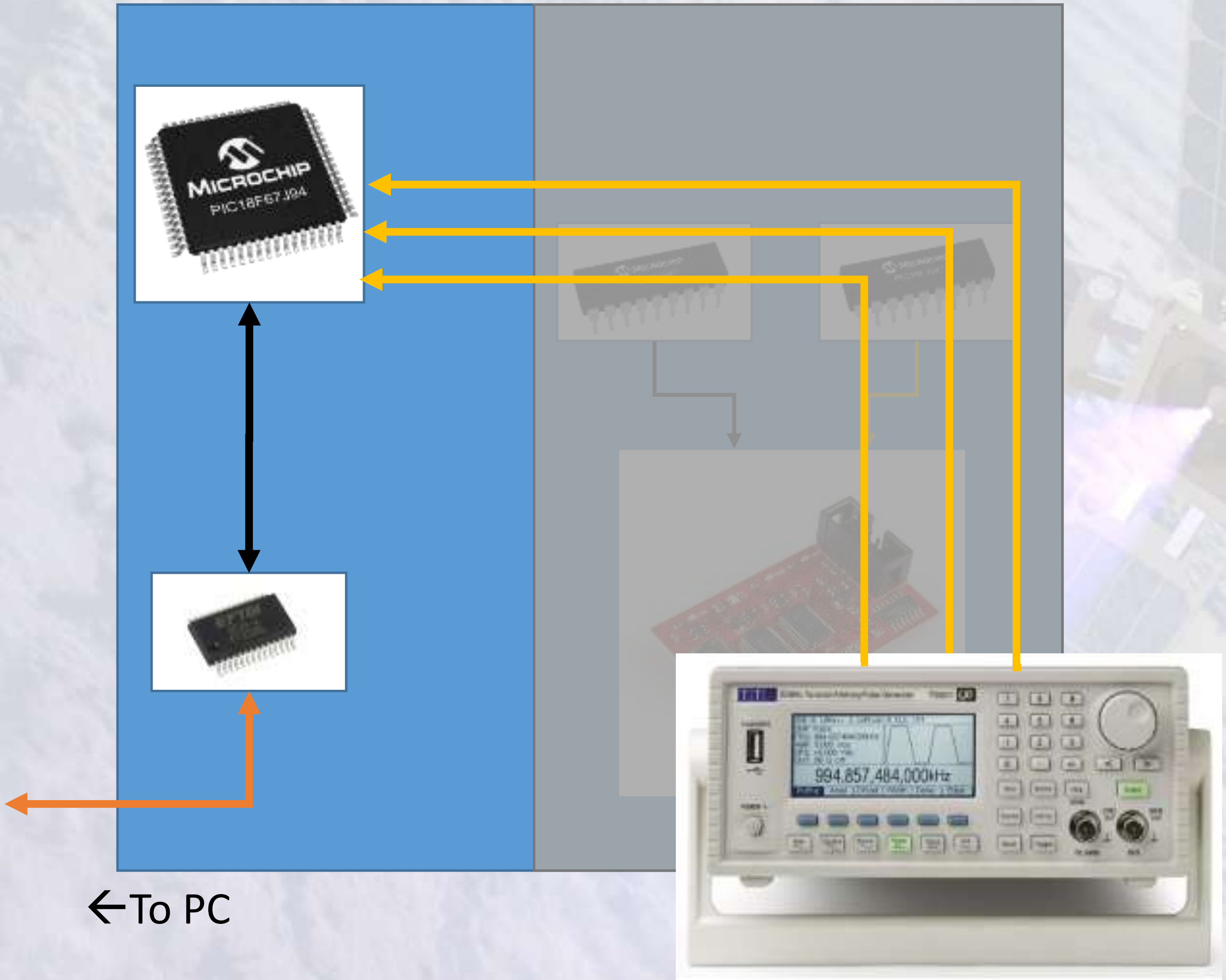


Goal: Verify Slave µC → ADCS Board

A: Use Bus Pirate to query over I2C for data, analyze given data

B: Repeat above for USART data transmission

Testing Board Verification – Step 4



←To PC

Goal: Verify Torque Rods → Master → FTDI → Matlab

A: Use a <u>known</u> PWM signal, capture via MµC. Send TMRH/L from MµC into FTDI, have Matlab verify dt

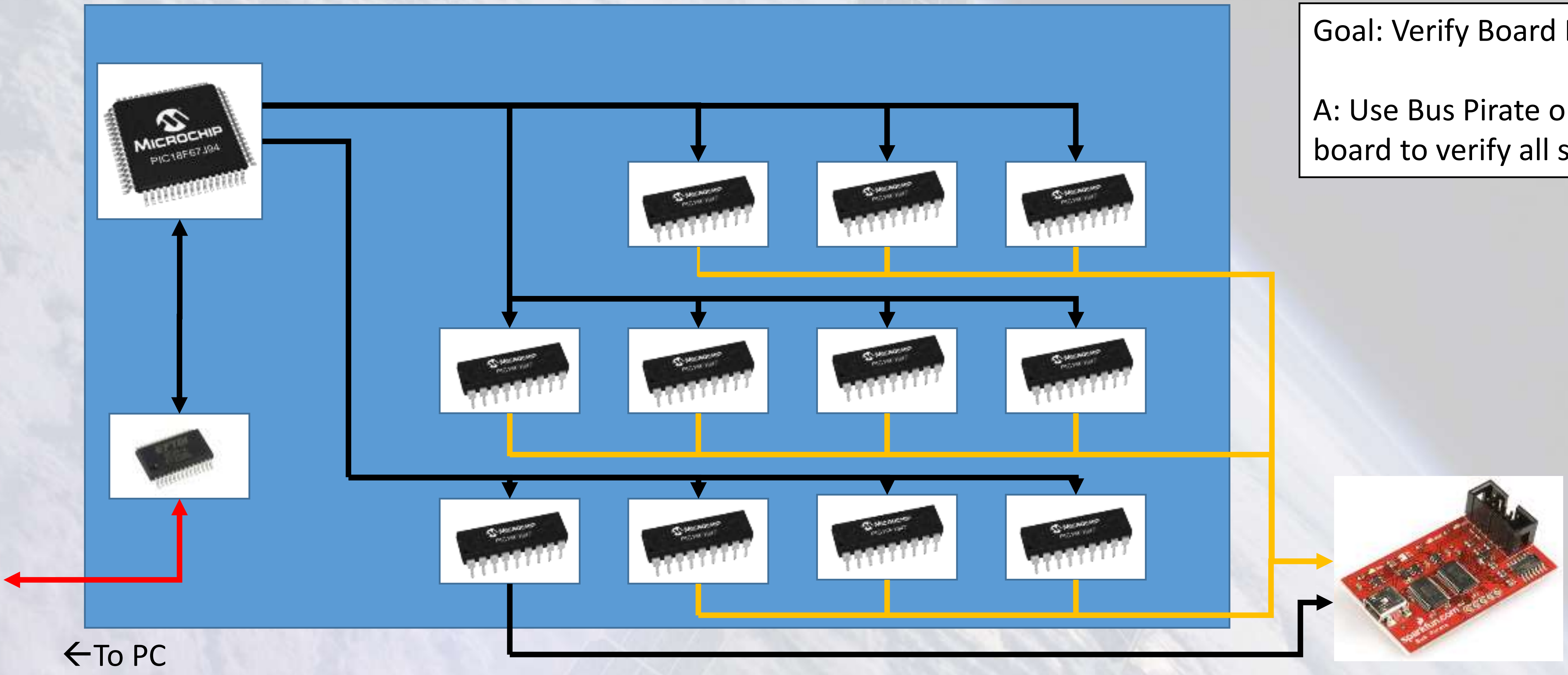
B: Repeat (a) with use of 3 PWMs (varying duty cycle, identical frequency)

C: Check interrupt logic via:

- i. Capturing 3 PWM signals
- ii. Verifying ability to send signal to Matlab
- iii. Send data vector from Matlab while obtaining PWM signals

*Design not to scale

Board Verification – Step 5

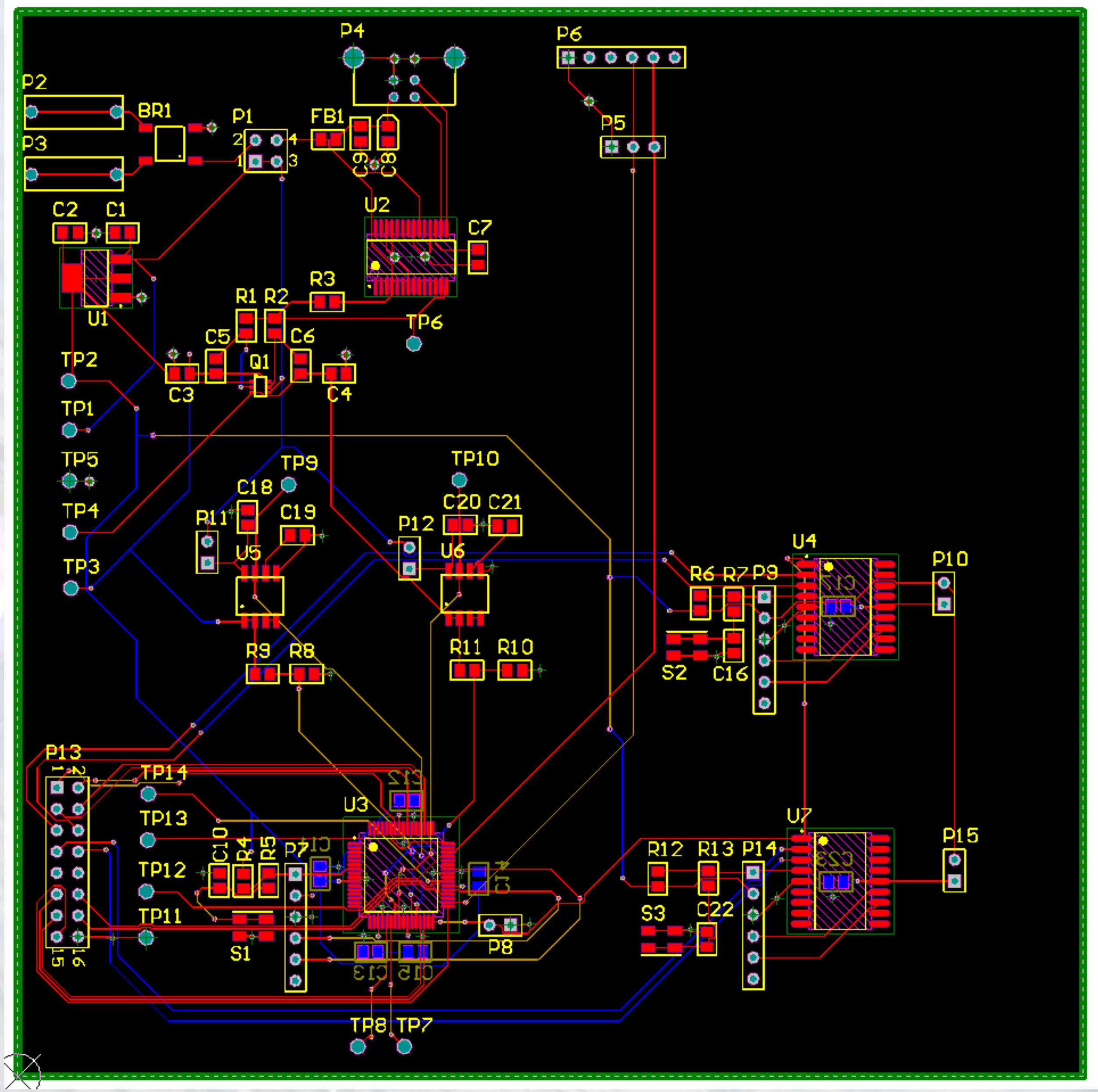


Goal: Verify Board Design

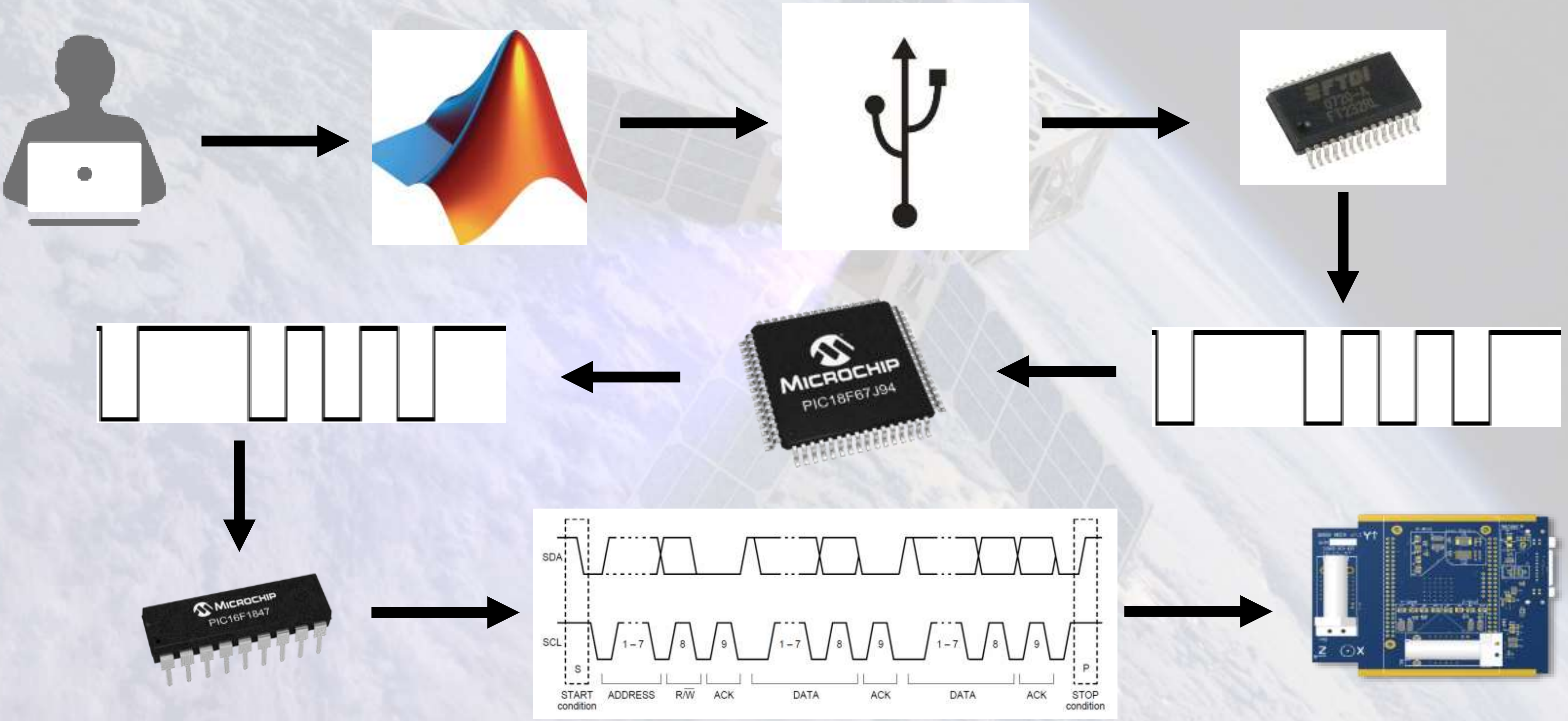
A: Use Bus Pirate on final board to verify all signals

*Design not to scale

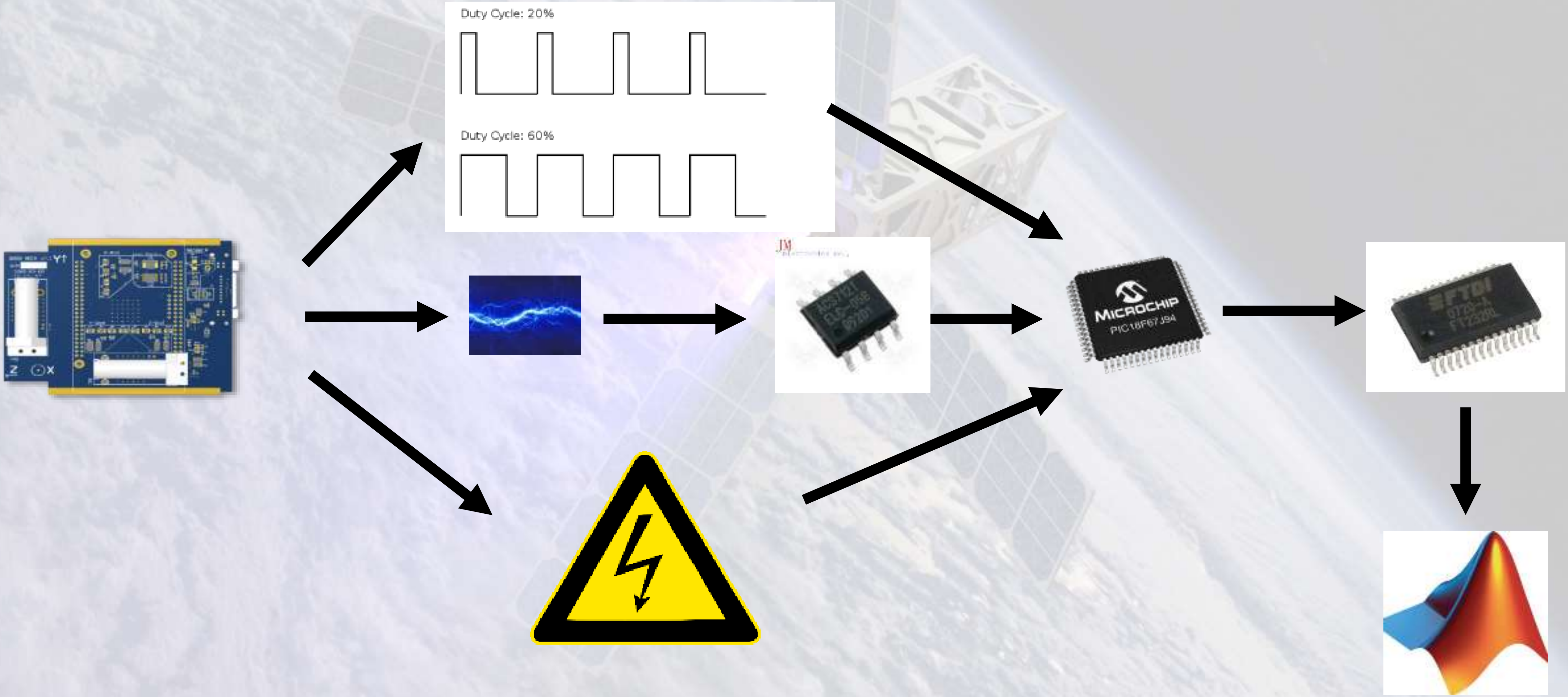
Altium Board Layout



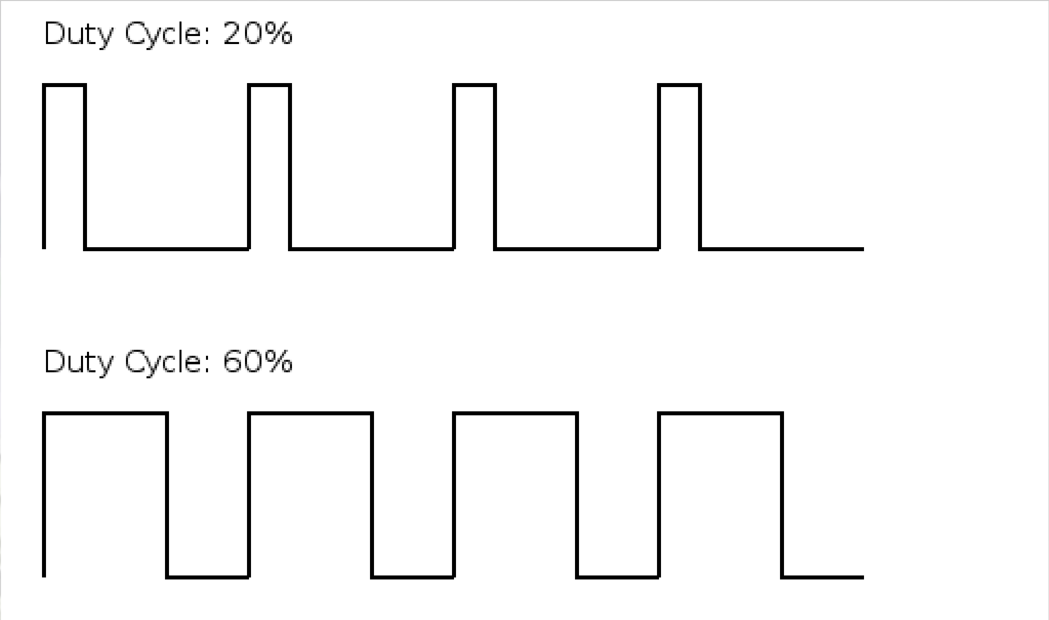
Overall Data Flow



Overall Data Flow

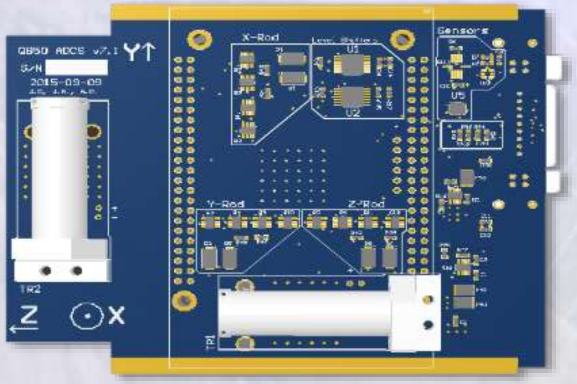


PWM Calculation



Torque Rod Pulse Width Modulation

- Known 1 KHz rate
  - Capture rising and falling edge
  - ~12 instructions at 1.25e-7 rate
  - Max error from oscillator **% error**



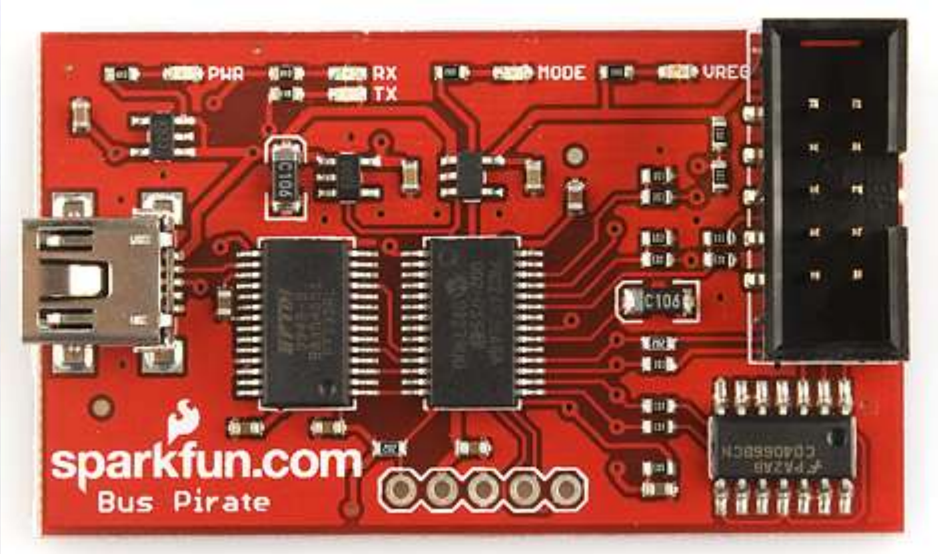
Off-Ramps

- Duty Cycle updates at maximum of 10 Hz
  - Don’t need to verify each point to get duty cycle
- Use on-board math to check time deltas
  - Reduce data sent back to Matlab

SparkFun Bus Pirate
TOL-09544 ROHS

- External component to test various protocols

    -Supports I2C and USART
- Connects into PC
- Can sample up to 40MHz signal
- Can also be used to verify PWM signal
- Appears as virtual COM port over USB



Timing Diagram – Master Controller

Data Process:

High Priority Interrupt

- Capture PWM Timing Signal
- Triggered via rising/falling edge from Torque Rods

Low Priority Interrupt

- Read data from PC
- Transmit data from PWM/ADCs
- Sort new data into appropriate locations

USART Data Transmission

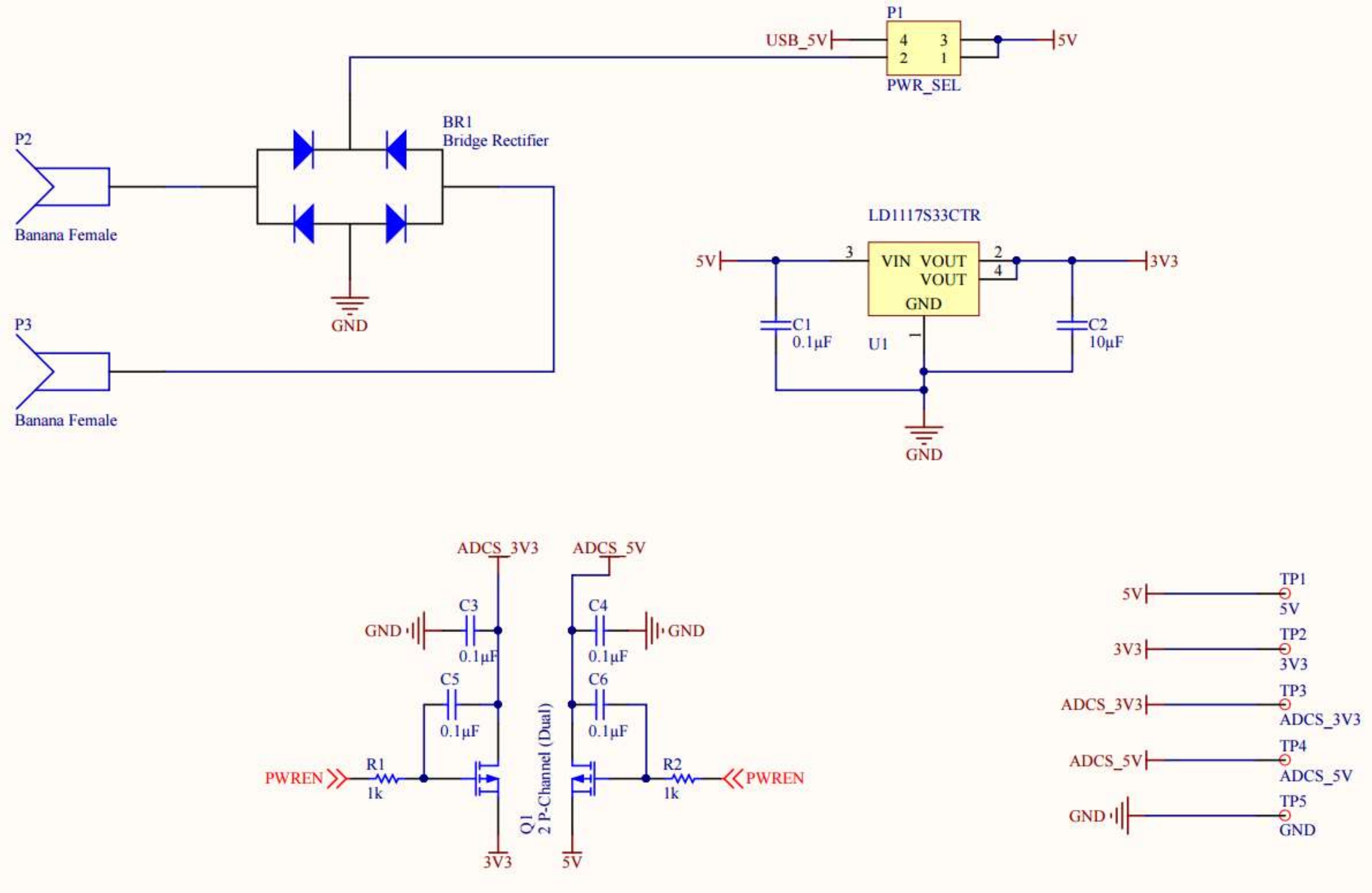
- Repeat sending of data in known series through to Slave Controllers

Timing Diagram – Expected Instructions

	Expected Iterations	Data Frequency	Expected Bits / Iteration	Total anticipated time
High Priority Interrupt	600	12 instructions	2	0.0009
Low Priority Interrupt -Receive	1	256 KHz	880	0.0034
Low Priority Interrupt -Transmit	1	256 KHz	1200	0.0469
USART Data Transmission	1	256 KHz	1100	0.0043
			Total:	**.0555 seconds**
			% use	**55.5%**

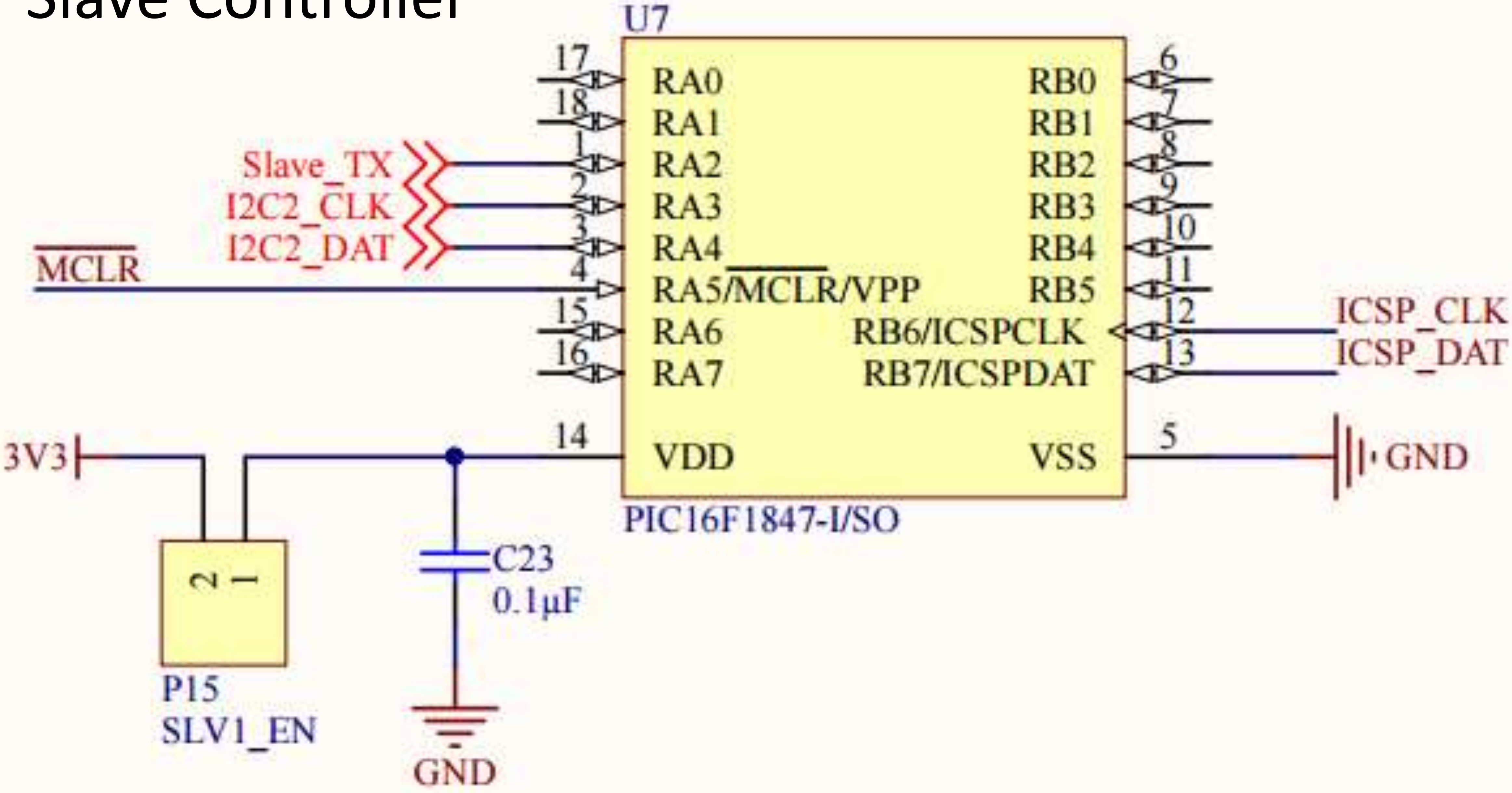
Operating at less than 60% capacity!

Power

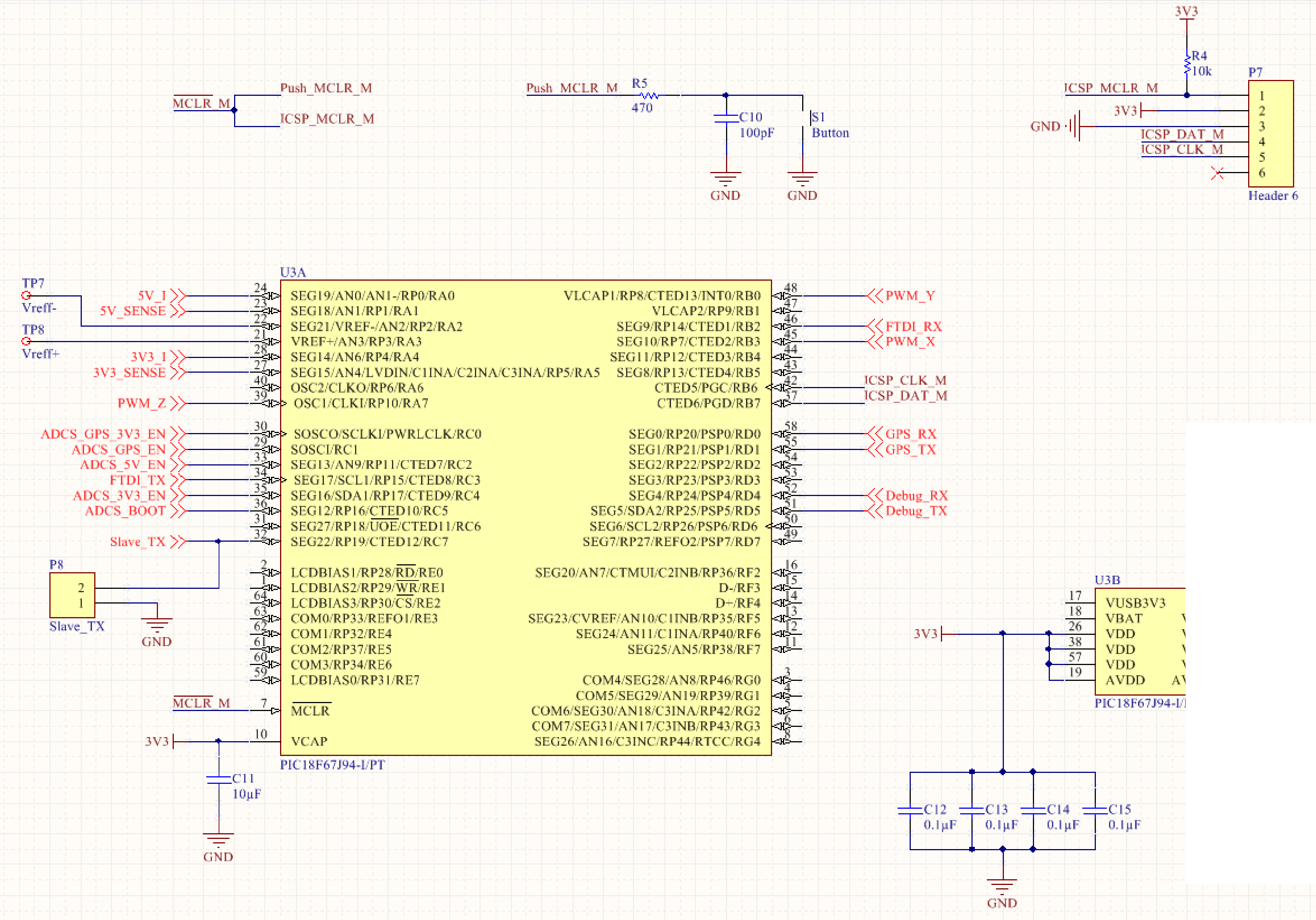


P1
USB_5V
5V
PWR_SEL
BR1
Bridge Rectifier
P2
Banana Female
P3
Banana Female
GND
LD1117S33CTR
VIN VOUT
VOUT
GND
U1
C1
0.1µF
C2
10µF
3V3
ADCS_3V3
ADCS_5V
C3
C4
C5
C6
0.1µF
PWREN
R1
1k
R2
1k
Q1
2 P-Channel (Dual)
TP1
TP2
TP3
TP4
TP5

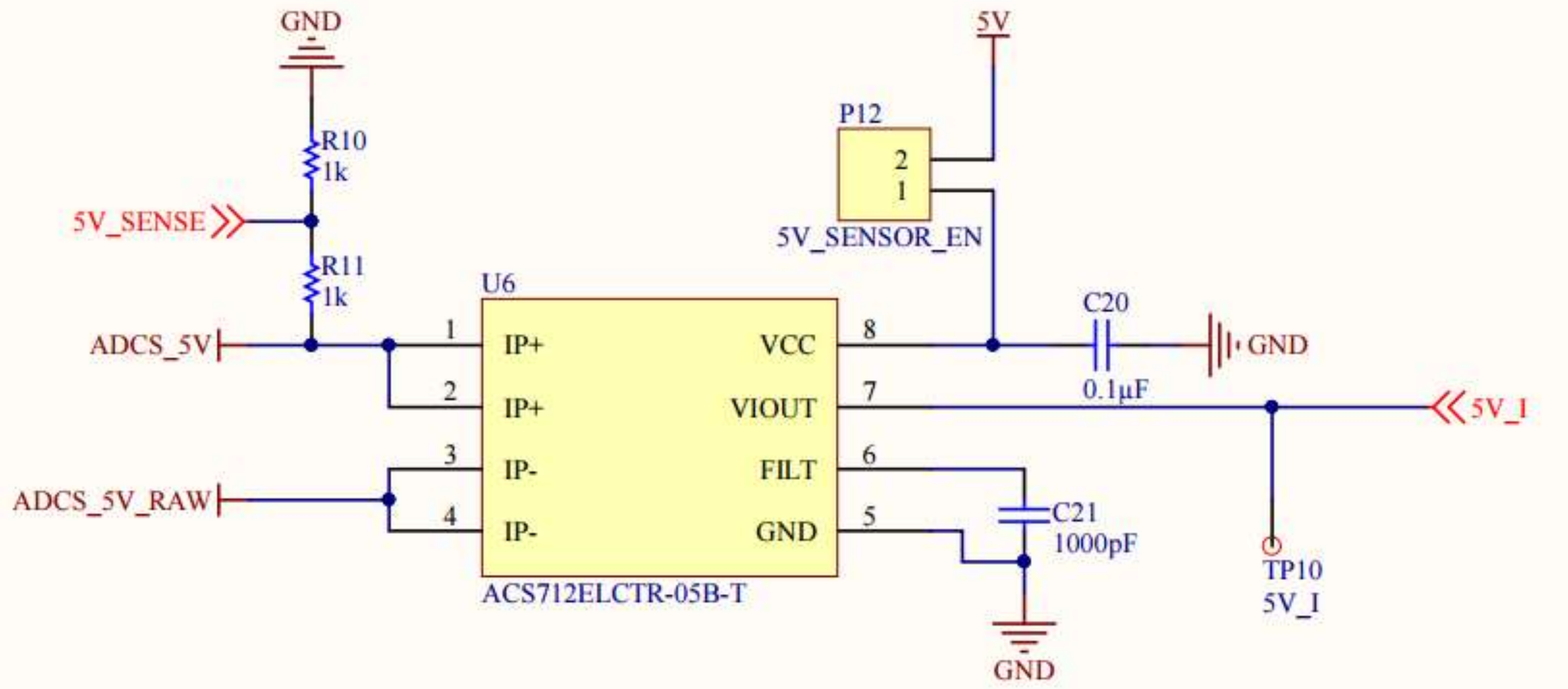
Slave Controller



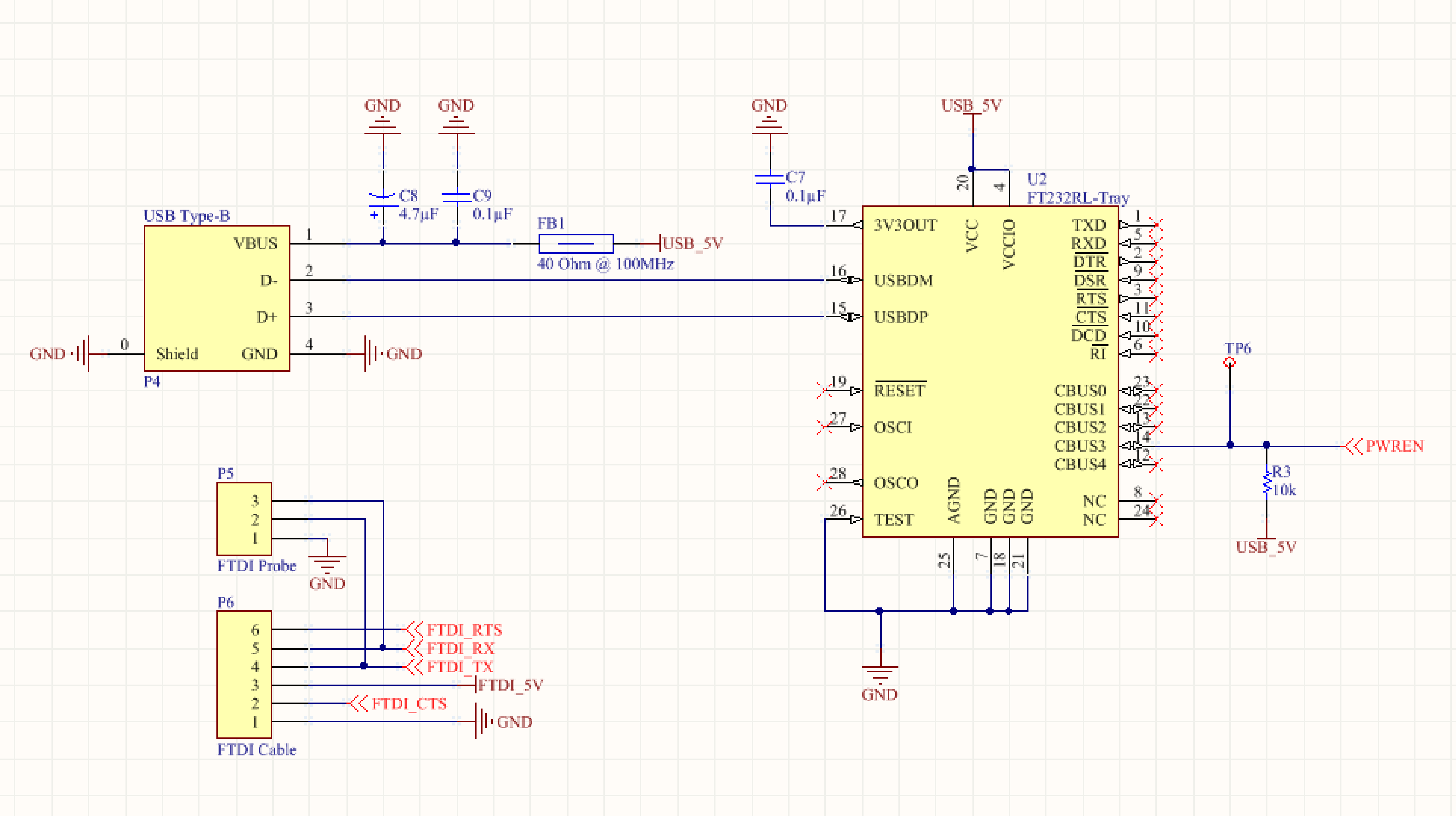
Master Controller



Current Sensor

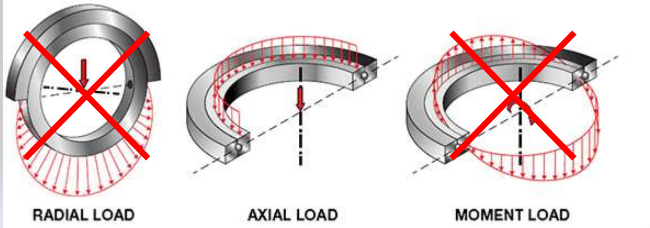


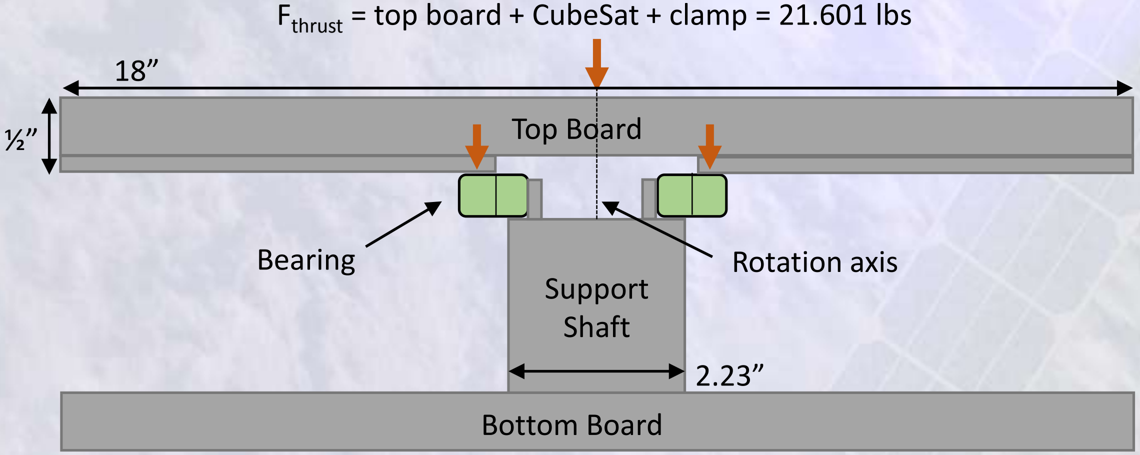
USB Schematic

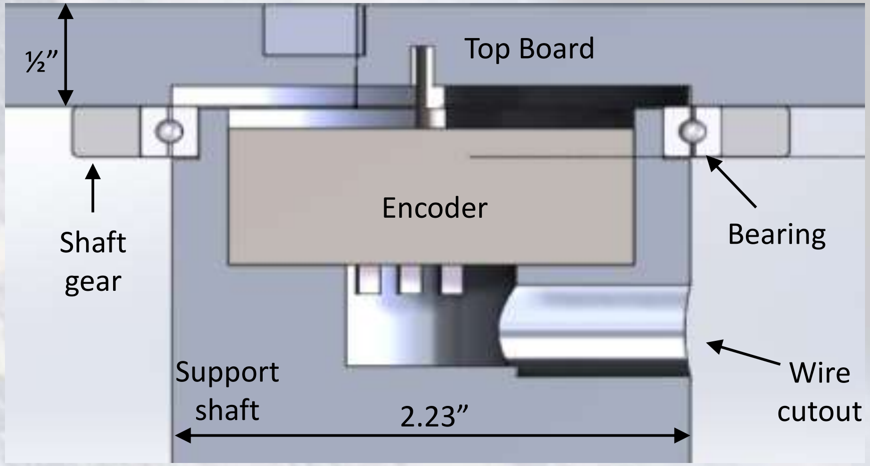


Turntable: Force and Moment Analysis

- CG of CubeSat is in 0.4” sphere of geometric center
- Geometric center aligned with rotation axis of board and within diameter of support shaft = no moments produced
- Combination ball-thrust bearing supports axial load
  - Thrust load capacity = 790 lbs
  - Moment load capacity = 430 in*lbs
  - Board can roughly support 45 lbs point load on perimeter



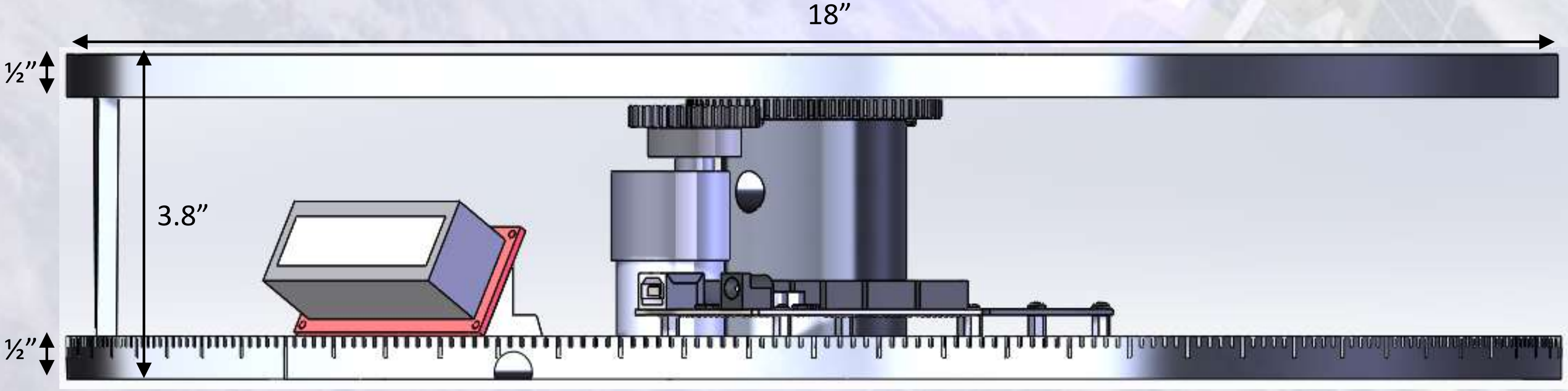




Mission Introduction | Project Description | Interface Board | Sun Sensor Table | Helmholtz Cage Test | Summary

Turntable: System Overview

- Total weight = 25.8 lbs (no clamps and CubeSat)
- Motor and encoder secured in friction fit cutouts
- Arduino and motor driver secured with nylon spacers/screws
- LCD superglued to acrylic support
- Everything else secured with machine screws



Sun Sensor Calibration Table – Torque Calculation

τ_R = torque required on board

ρ = density of Aluminum 6061 = 2700 kg/m^3

r = radius of board = 9" = 0.2286 m

t = thickness of board = ½" = 0.0127 m

m_{cu} = max mass of CubeSat (3U) = 3.6 kg

m_{cl} = max mass of clamps = 0.5651 kg

C_f = max bearing coefficient of friction = 0.0015

g = gravity = 9.81 m/s^2

m_t = max total mass (kg)

$$m_t = \rho * \pi * r^2 * t + m_{cu} + m_{cl} = 9.7946\, kg$$
$$\tau_R = C_f * m_t * g * r \approx 0.0329\, N * m = 0.2912\, in * lbs$$

Sun Sensor Calibration Table – RPM Calculation

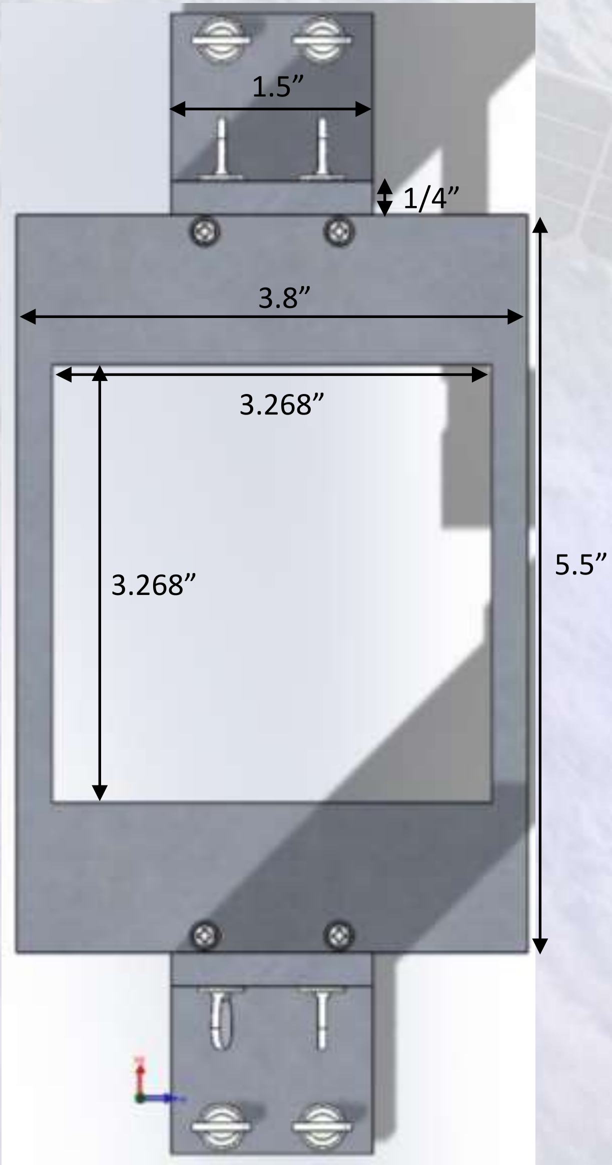
Need at least one sample per degree:

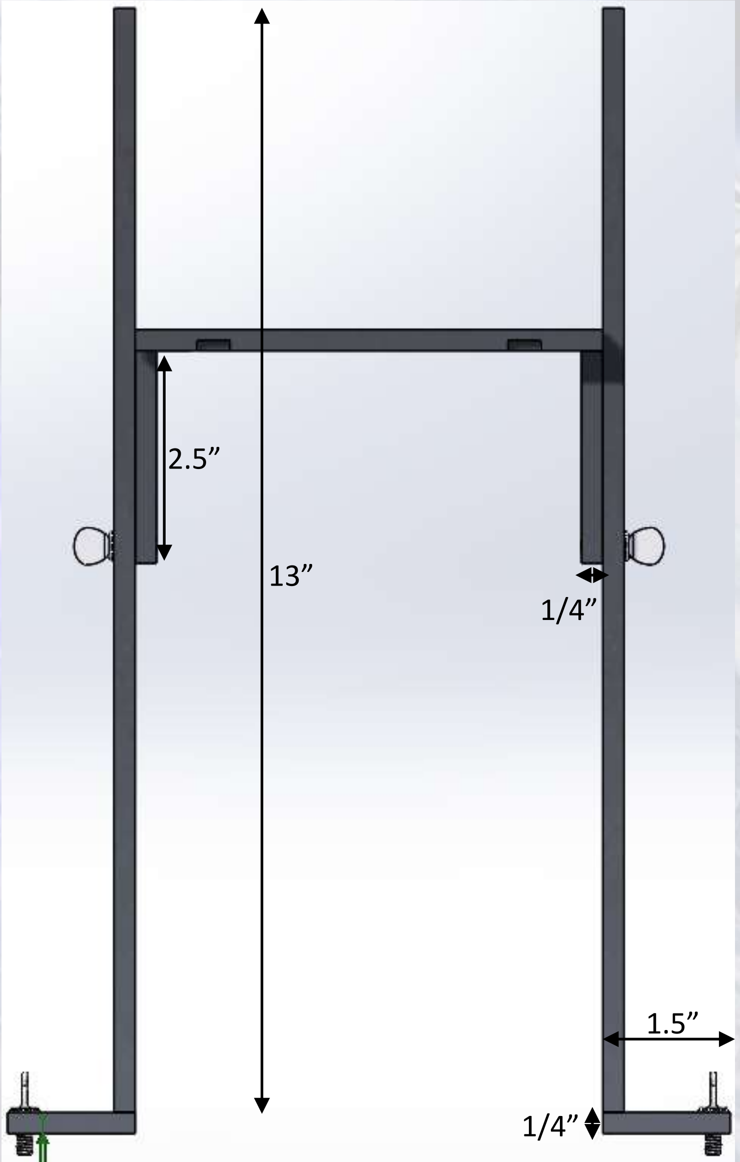
$$10\ Hz = \frac{10\ \cancel{samples}}{1\ second} * \frac{1\ \cancel{degree}}{1\ \cancel{sample}} * \frac{1\ rotation}{360\ \cancel{degrees}} = \frac{1\ rotation}{36\ seconds} = \frac{5}{3} RPM$$

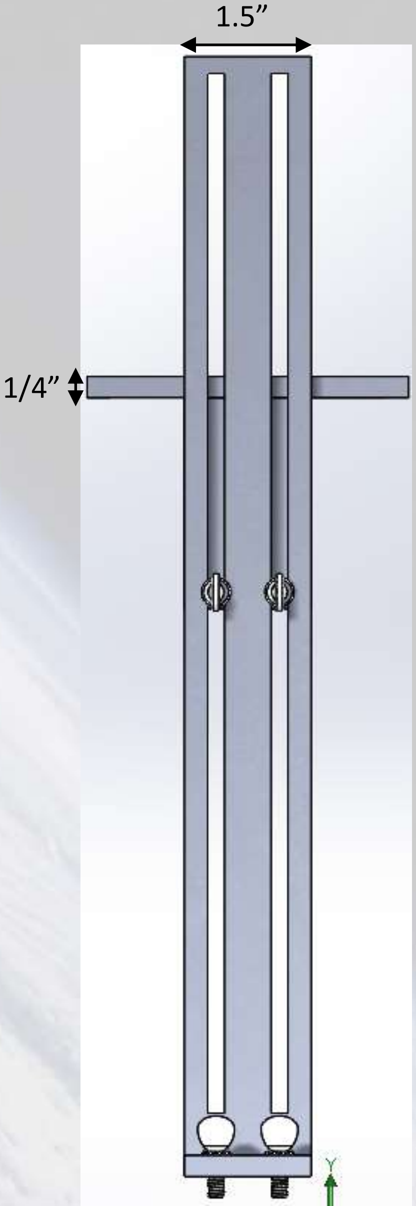
$$Gear\ Ratio = \frac{Teeth_{shaft}}{Teeth_{motor}} = 2$$

$$RPM_{board} = \frac{5}{3} \geq \frac{RPM_{motor}}{Gear\ Ratio} = \frac{1}{2}$$

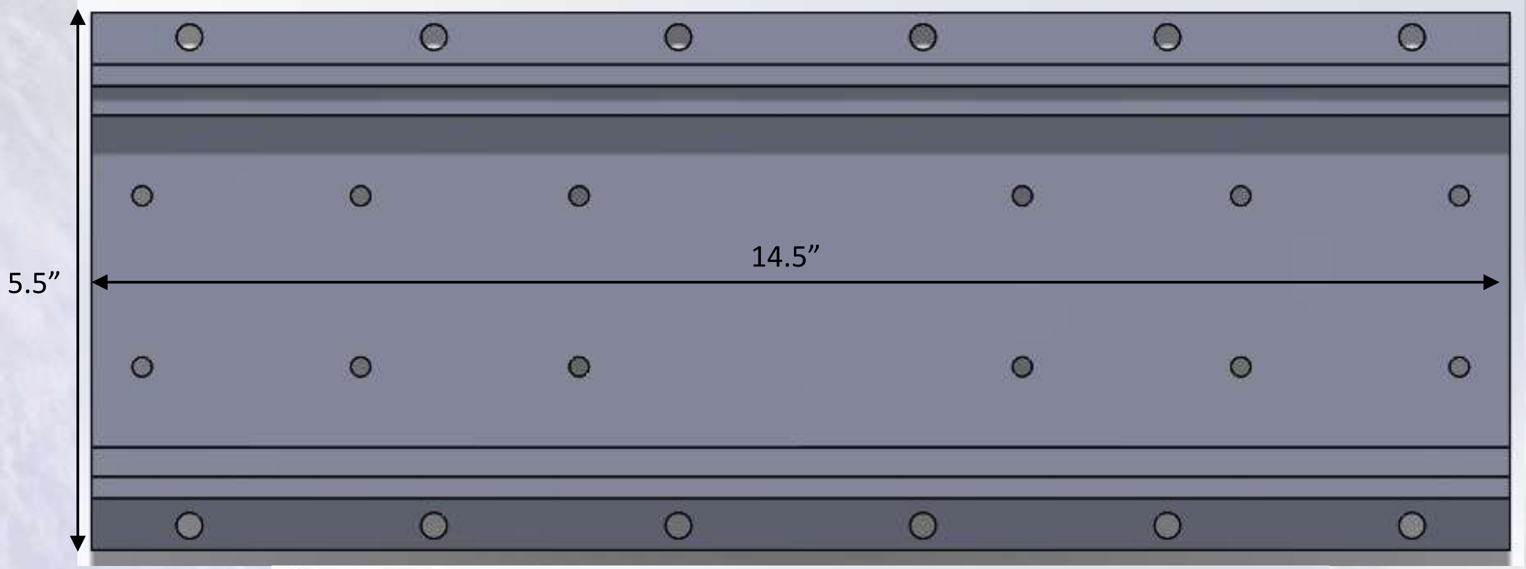
Turntable: Attachment Dimensions - Vertical







Turntable: Attachment Dimensions - Horizontal



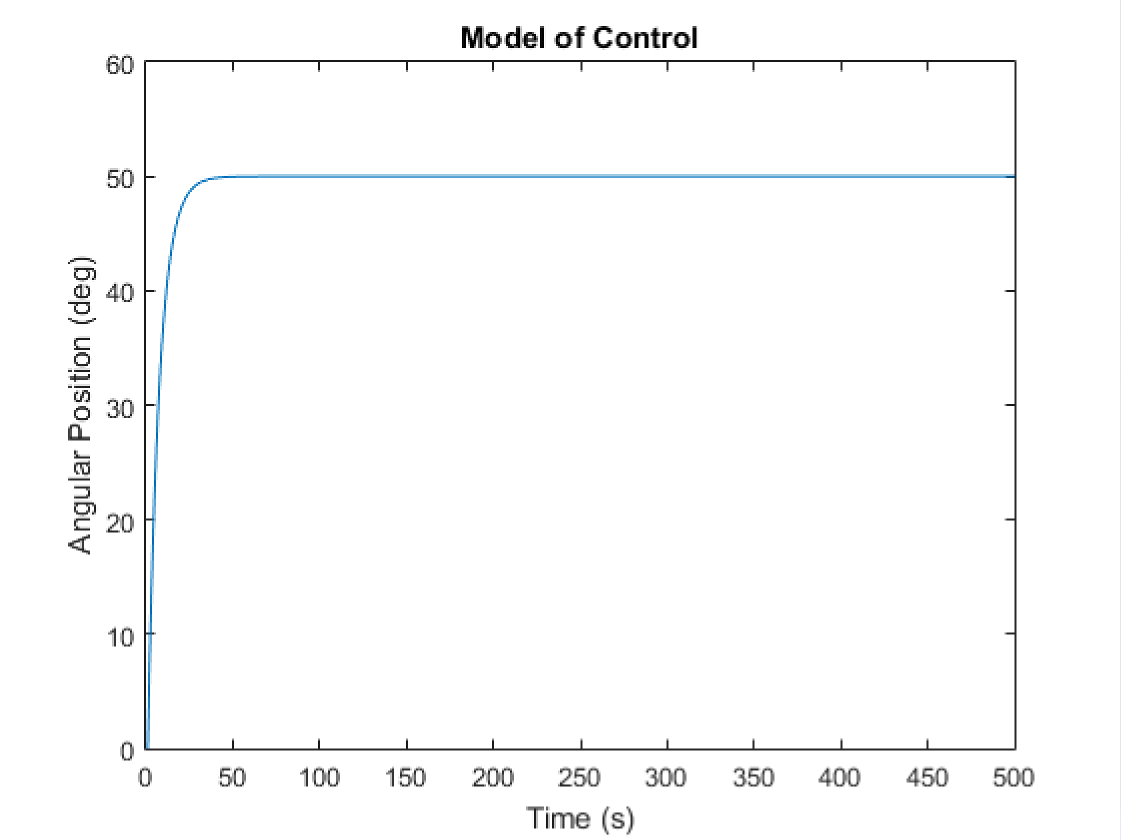
Turntable: Part Numbers

Part	Manufacturer	Part Number
Magnetic Encoder	Bourns	AMS22U
DC Motor	Sparkfun	ROB-12219
LCD	Sparkfun	LCD-09066
Motor Driver	Pololu	755
Microcontroller	Arduino	Arduino Mega 2560
Bearing	McMaster-Carr	6656K11
Gear – motor	McMaster-Carr	6325K65
Gear – board	McMaster-Carr	6325K67
Reflectance coating	Avian Technologies LLC	Avian Black-S

Turntable: Pin Mapping

Purpose	Ardunio	Encoder	LCD	MotorDriver
Communicate with Computer	USB			
Power Encoder	5V	5V		
Power LCD	3.3V		3.3V	
Ground Encoder	GND	GND		
Communicate with Encoder	Pin 97	Analog		
Communicate with LCD	Pin 3		RX	
Communicate with motor Driver	Pins 6,7			PWM,DIR

Turntable: Control



- V_{in} limited to 12V

- $V_{in} = k_p(\theta_d - \theta)$
- $\tau = f(V_{in})$
- $\Theta = \frac{\tau * t^2}{2 * I}$

- Takes 32s to get within 0.5 deg of 50 deg
- Takes 17s to get to 50deg at max torque

Helmholtz Cage Testing Structure: Backup Calculations

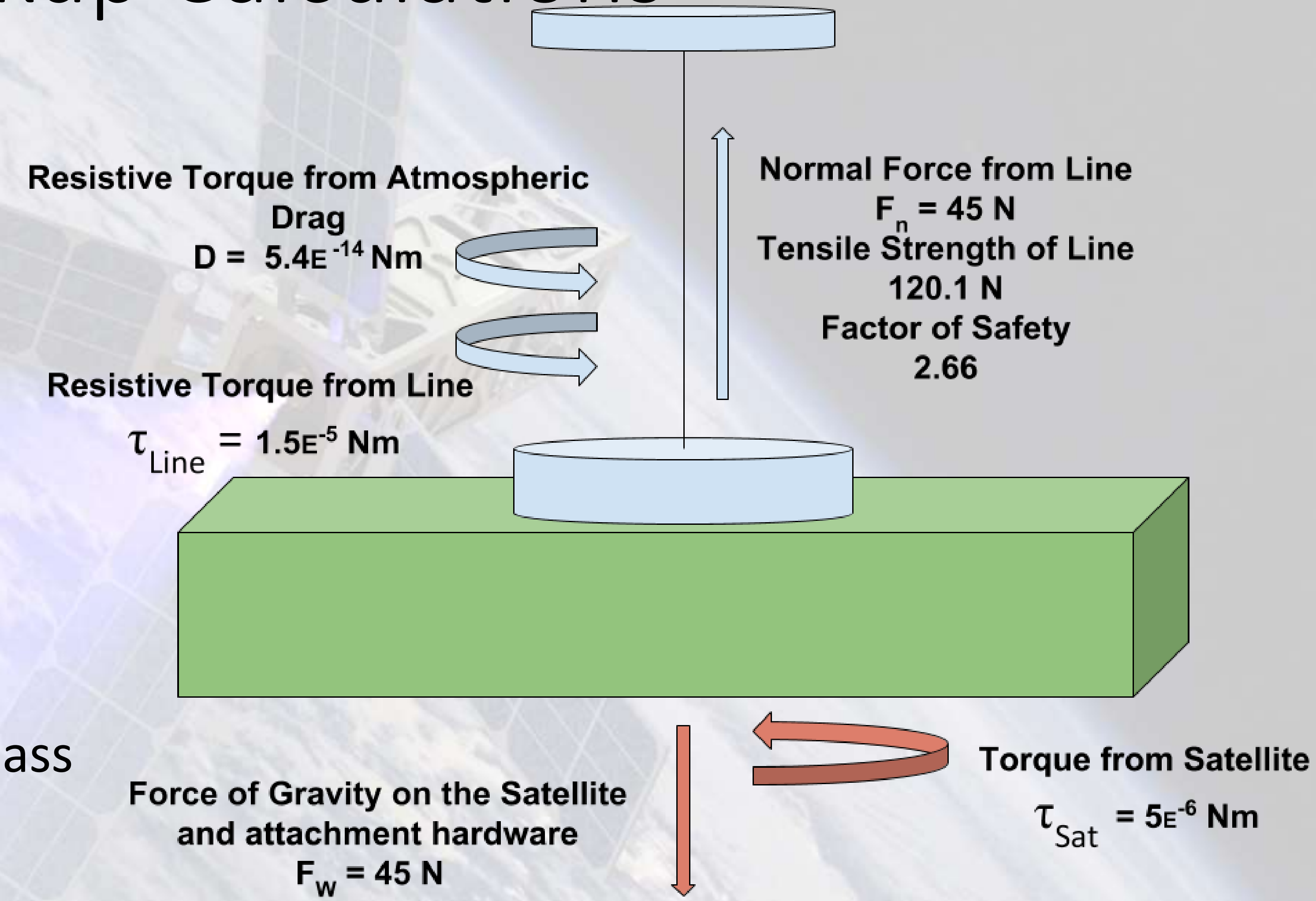
$M_D = \rho*\alpha^2*t^2*h*L^4*C_D / (64)$

- Assume $C_D = 2.05$
- Assume Moment of Inertia of a hollow rectangular prism

$\tau_{Line} = 2*\theta*I*t^{-2}$

- Assumes no initial position
- Assumes no initial velocity
- Tested with mass model at 7 ft
- 12 trials done with 3.6 kg mass
- 4 trials done with 5.6 kg mass
- Similar torque values for each mass

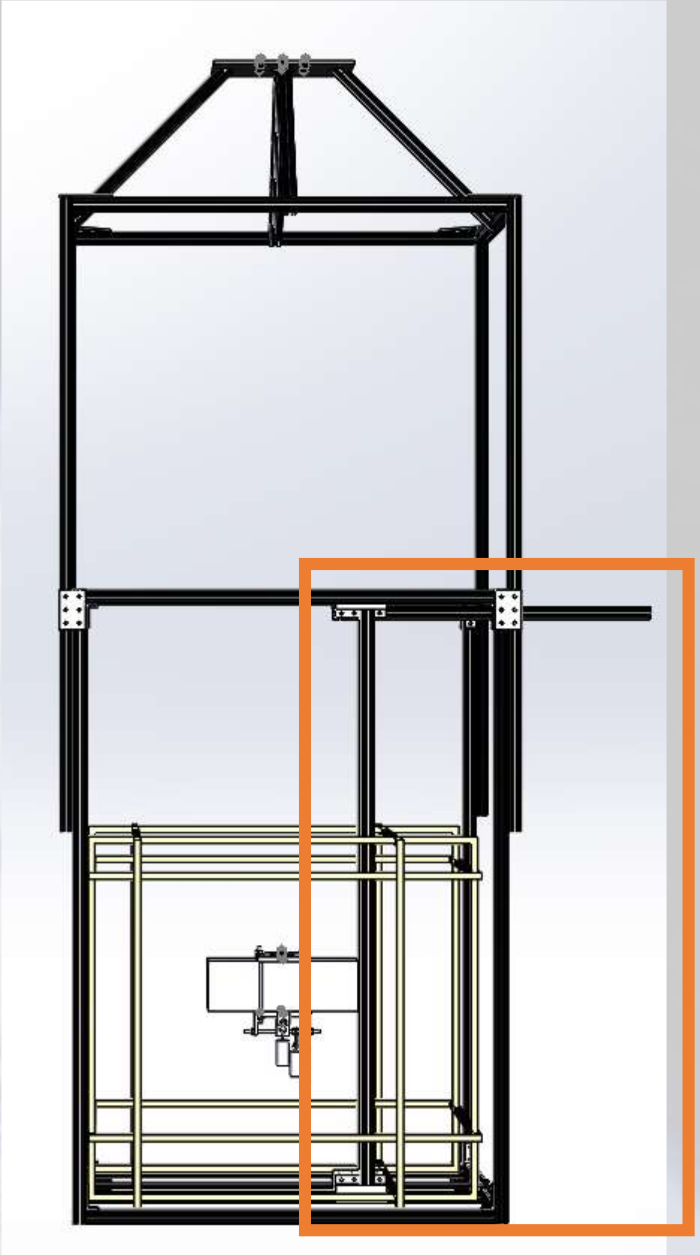
$\tau_{Sat} = \mu \times B$



$\tau_{Line} > \tau_{Sat} \Rightarrow$ Satellite will not move on its own

Helmholtz Cage Testing Structure: Locking Mechanism

Engaged **after** satellite is **hand-spun**, **before release**



Helmholtz Cage Testing Structure: Backup Calculations - Torque from Satellite

Turning Authority (Ta) = 0.1 Am2 = 0.1 J/T
Magnetic Field Strength (B) = 0.5 Gs = 5_E^{-5} T

Maximum Torqe = B * Ta = 5_E^{-6} Nm

Helmholtz Cage Testing Structure: Backup Calculations - Tilting Impact

L_0 = initial length of line
d = diameter of line
G = modulus of rigidity
E = modulus of elasticity
v = Poisson's Ratio
σ = Normal Stress
ε = Strain
F = load on line
A_{CS} = cross-sectional area of line

Helmholtz Cage Testing Structure: Backup Calculations - Line Resistive Torque

τ_{Line} = Resistive Torque from the line

I = mass moment of inertia of the rod

α = angular acceleration of the rod

r = cross-sectional radius of the line

θ = angular deflection = 360°

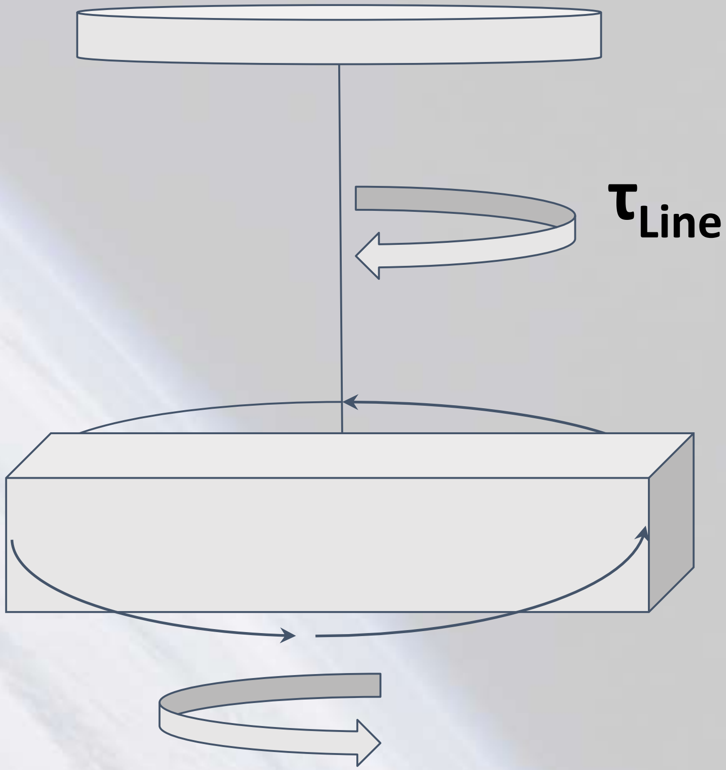
t = time for the rod to rotate θ°
- found experimentally

$$\tau_{Line} = I * \alpha$$

$$I = m/12 * (h^2 + w^2)$$

$$\alpha = 2 * \theta * t^{-2}$$

$$\tau_{Line} = 1.5E^{-5}\ Nm$$



Displace Satellite 360°

measure time (t) until satellite returns to inital

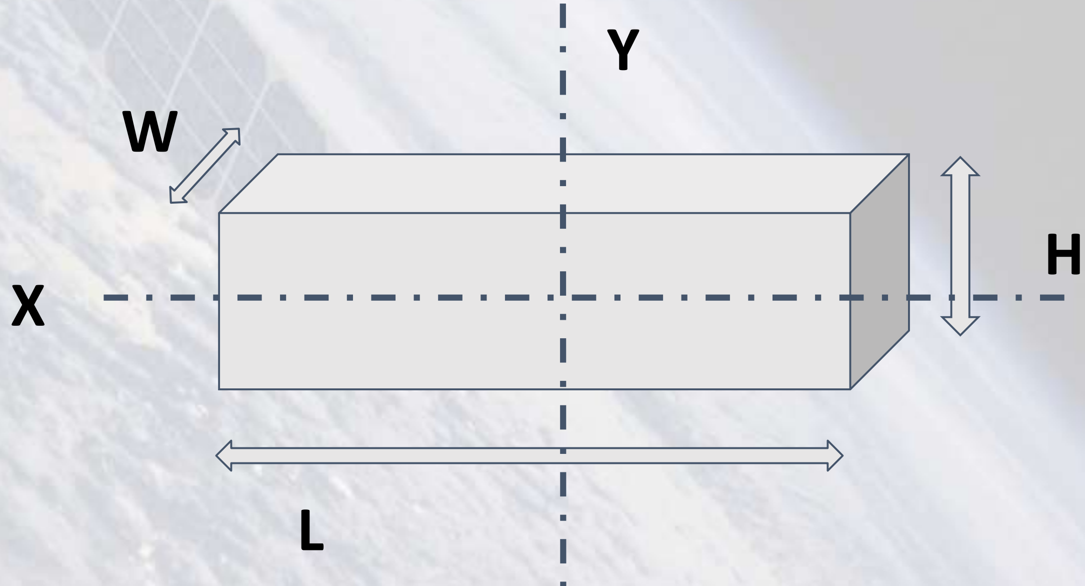
Helmholtz Cage Testing Structure: Backup Calculations - Satellite Acceleration

τ_{Sat} = Torque from satellite = 5E^{-6} Nm
I = mass moment of inertia about y axis
α = angular acceleration of satellite
ω = angular velocity of satellite
t = time satellite is accelerating
L = length of satellite = 30 cm
W = width of satellite = 10 cm
H = Height of satellite = 10 cm
m = mass of satellite = 3.6 kg
V = velocity of satellite edge

$$\tau_{Sat} = I * \alpha \longrightarrow \alpha = \tau_{Sat} / I$$

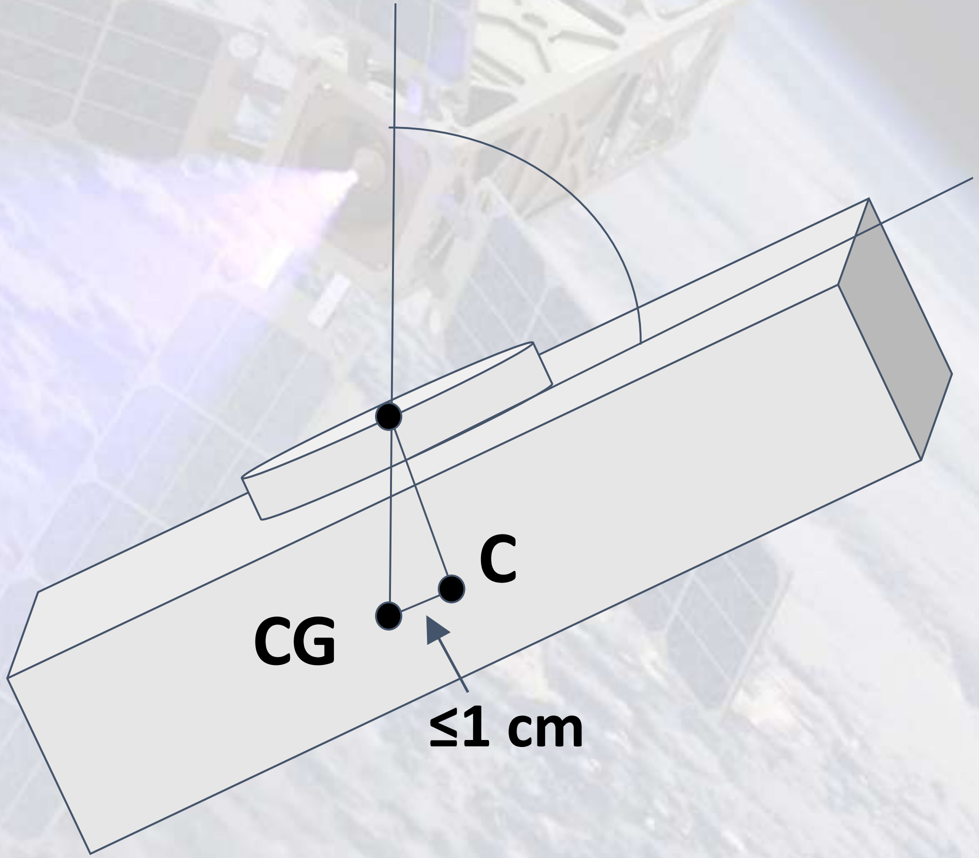
$$I = (m/12 * W^2_{outer} + m/3 * L^2_{outer}) - (m/12 * W^2_{inner} + m/3 * L^2_{inner})$$

$$V = \alpha * t * L * ½$$

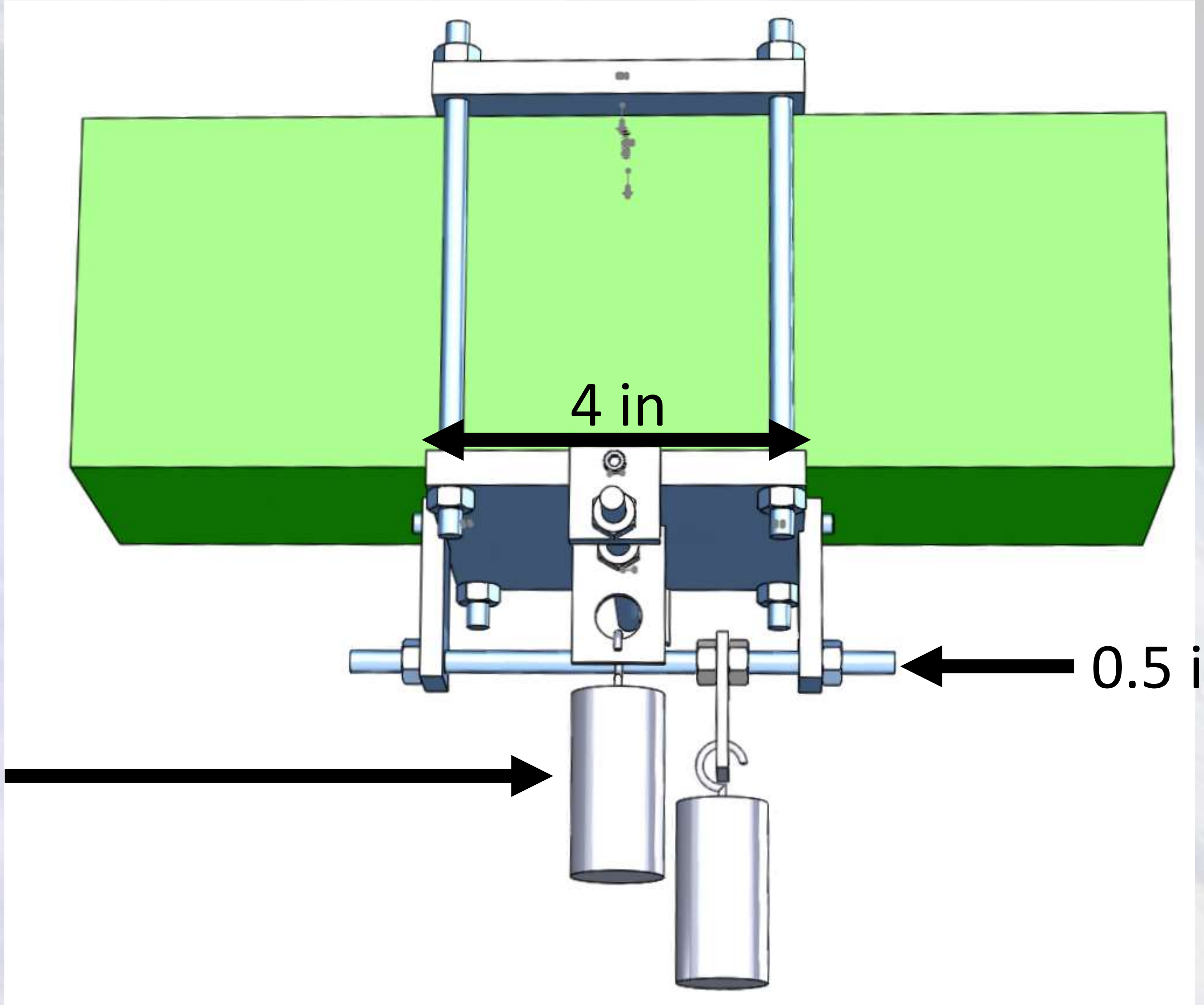


Helmholtz Cage Testing Structure: CG Adjustment

Center of Gravity (CG) ≠ Geometric Center (C)



Helmholtz Cage Testing Structure: CG Adjustment



Helmholtz Cage Testing Structure: CoG Adjustment

$$CG = \frac{M * D + m * d}{M + m}$$

$$m = \frac{-M \; * D}{-d} = 0.72 \; kg$$

G = Satellite Center of Gravity

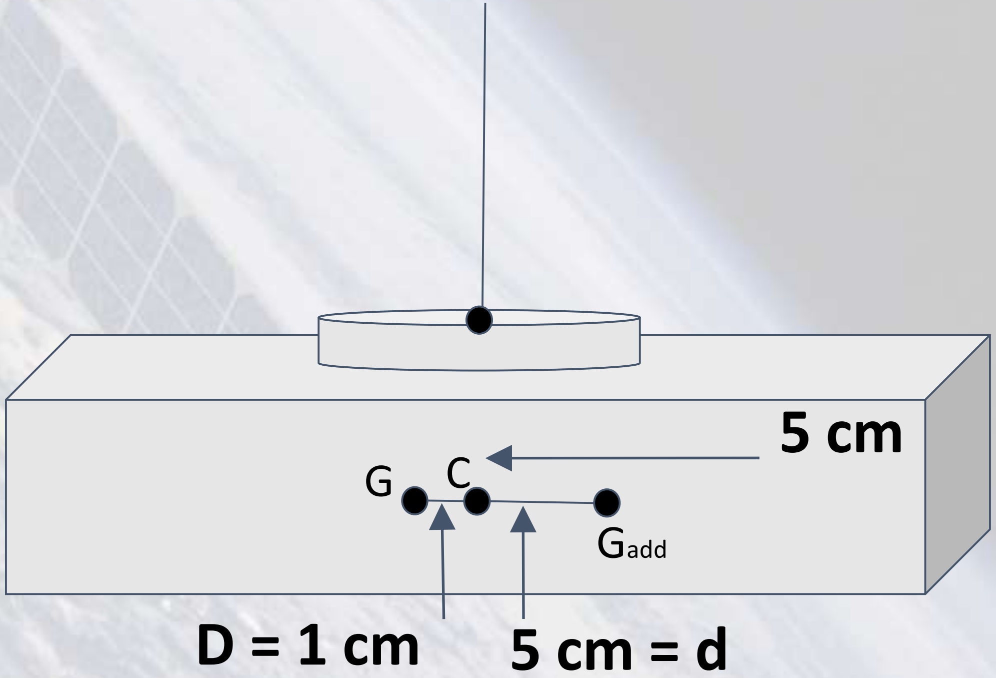
M = Satellite Mass = 3.6 kg (for 3U)

C = Geometric Center of Satellite

G_{add} = Added Mass Center of Gravity

D = Maximum Distance from G to C = 1 cm

d = Maximum Distance from G_{add} to C = 5 cm



Helmholtz Cage Testing Structure: Backup Calculations - Moment From Drag

D = Drag Force
C_D = Drag Coefficient of flat plate = 1.05 to 2.05

- assumed to be 2.05 to be conservative

ρ = density = 1.05 kg/m-3

- assumed to be standard atmosphere at 1500 m (5000 ft)

V = velocity of outermost satellite edge
A = Area of satellite side
M_D = Moment caused by Drag

$D = ½ * \rho * V^2 * C_D * A$

- V and A vary from the center to the edge of the satellite

$M_D = \rho * \alpha^2 * t^2 * h * L^4 * C_D / (64)$

- Drag was integrated over half of the satellite length

Helmholtz Cage Testing Structure: Backup Calculations - Moment From Drag

D = Drag Force

C_D = Drag Coefficient of flat plate = 1.05 to 2.05

- assumed to be 2.05 to be conservative

ρ = density = 1.05 kg/m-3

- assumed to be standard atmosphere at 1500 m (5000 ft)

V = velocity of outermost satellite edge

A = Area of satellite side

M_D = Moment caused by Drag

$D = ½ * \rho * V^2 * C_D * A$

- V and A vary from the center to the edge of the satellite

$F_{equivalent} = D * L / 4$

- Drag approximated by distributed load

$d = ⅔ * r$

$M_D = 2 * F_{equivalent} * d$

Helmholtz Cage Testing Structure: Backup Calculations - Moment From Drag

$D = \frac{1}{2} * \rho * V^2 * C_D * A$

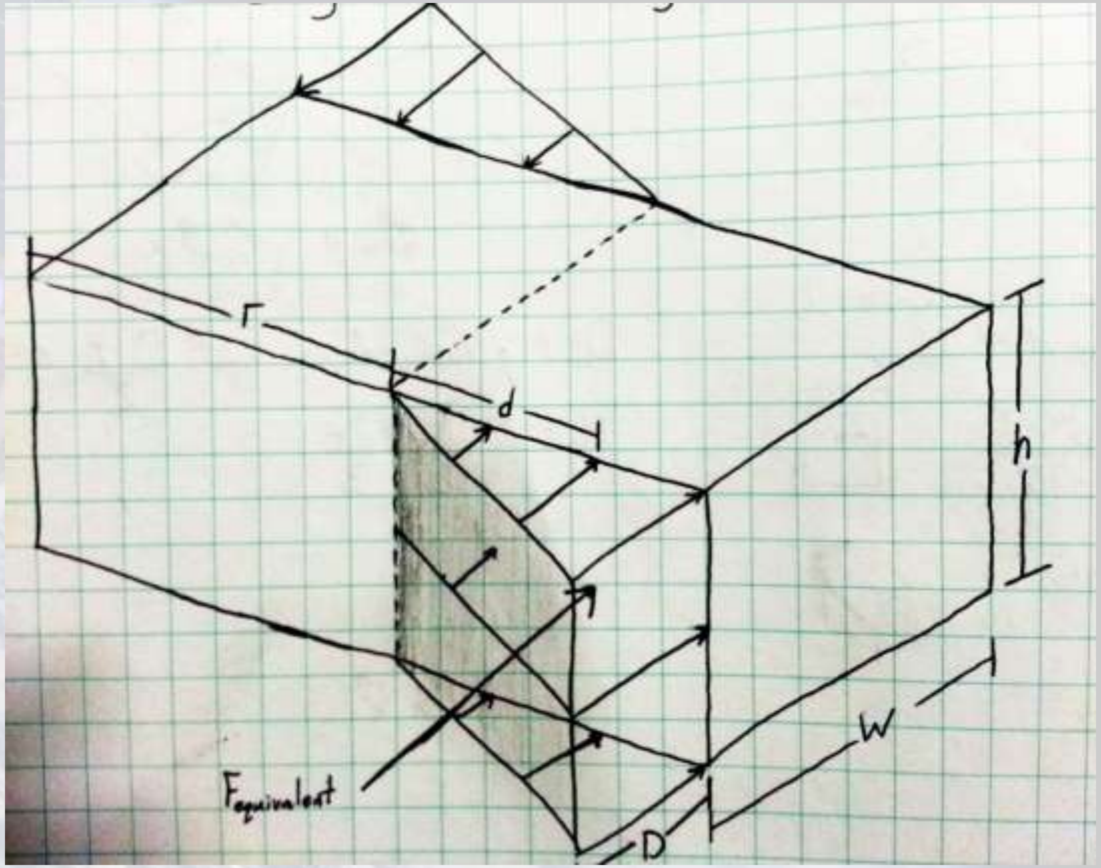
- V and A vary from the center to the edge of the satellite

$F_{equivalent} = D * L / 4$

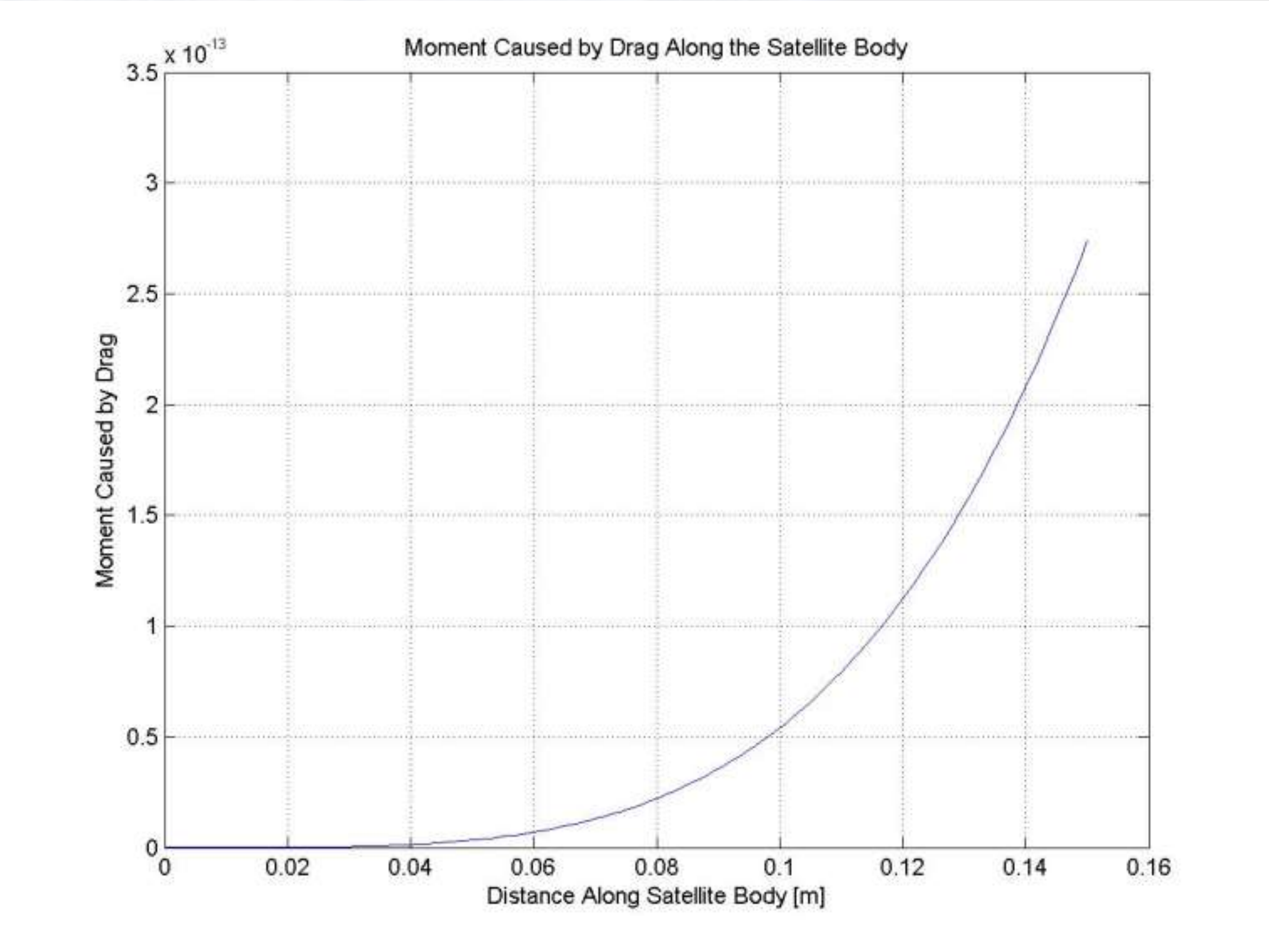
- Drag approximated by distributed load

$d = \frac{2}{3} * r$

$M_D = 2 * F_{equivalent} * d$

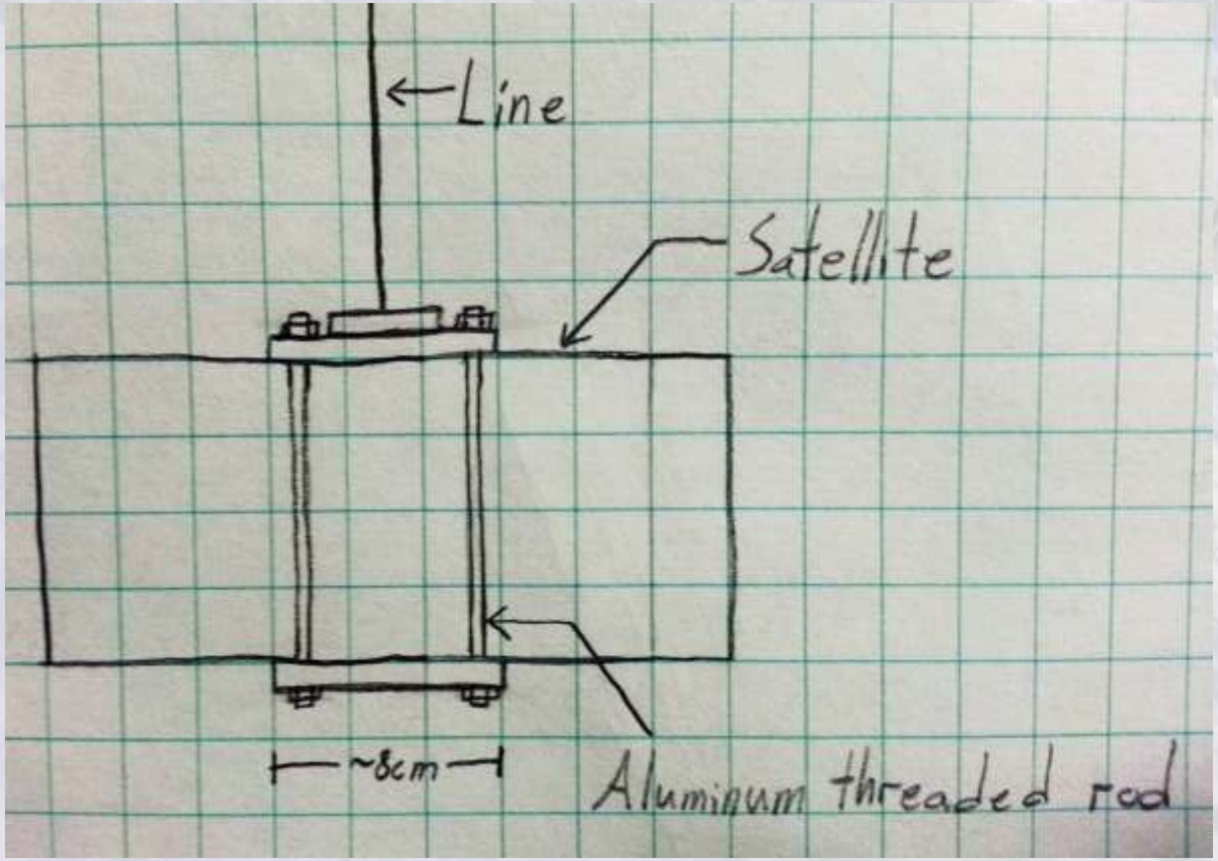


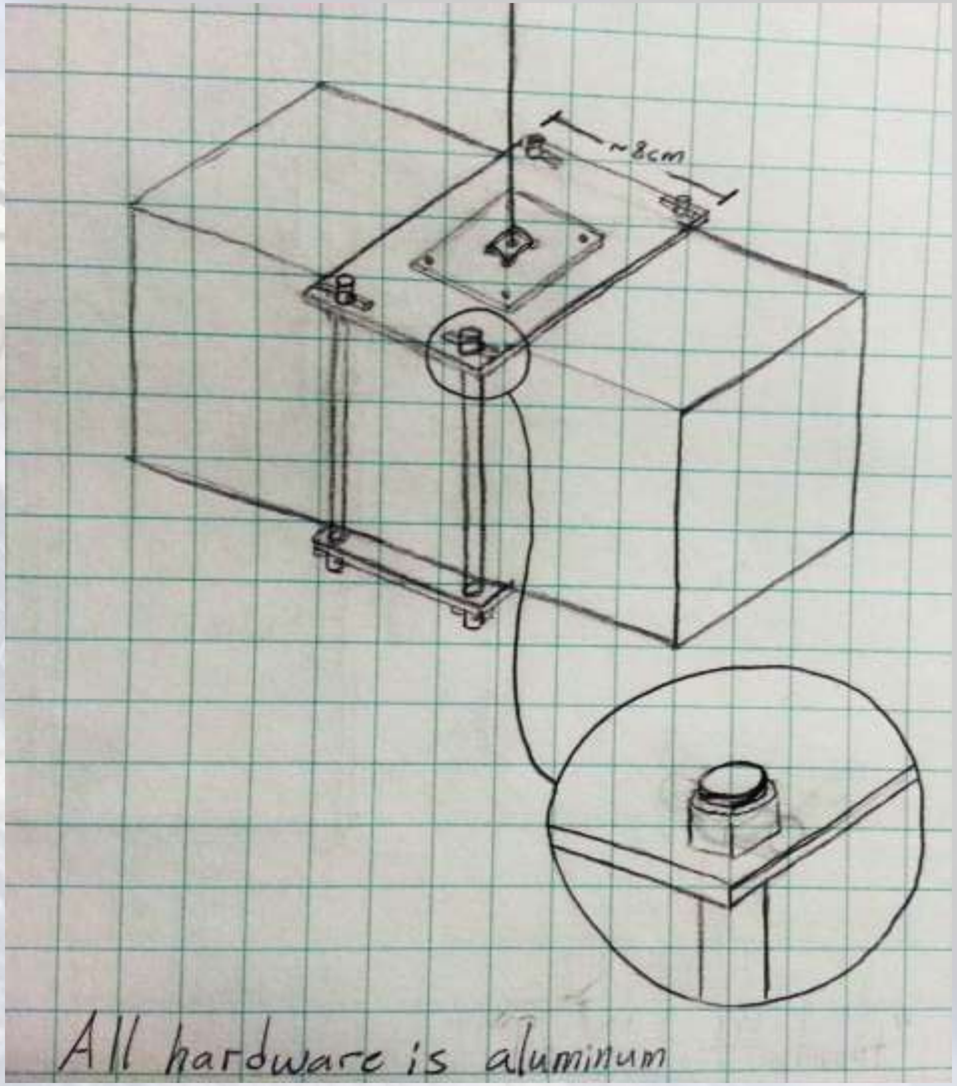
Helmholtz Cage Testing Structure: Backup Calculations - Moment From Drag



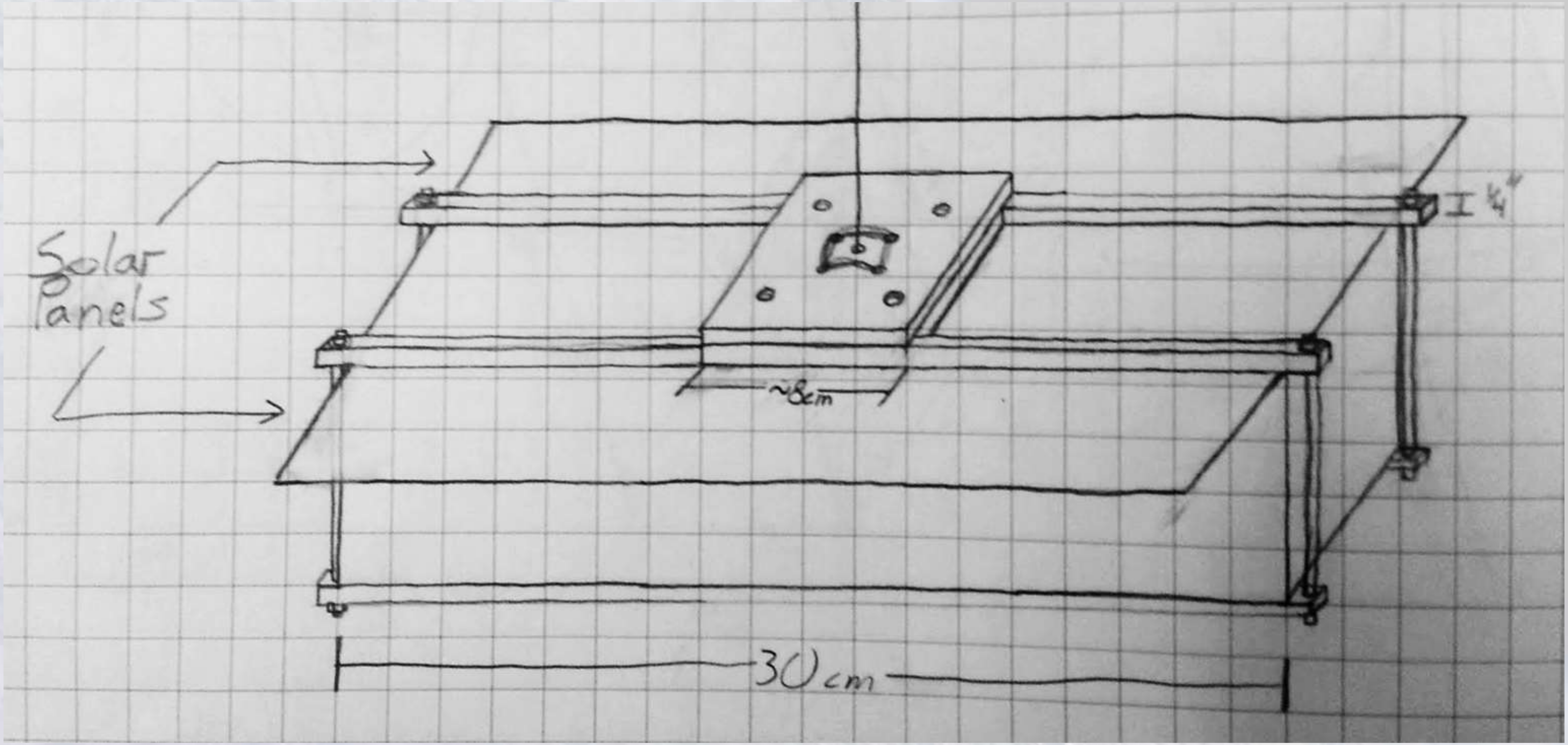
Helmholtz Cage Testing Structure: Backup - Attachment

Satellite Attachment Mechanism 1





Helmholtz Cage Testing Structure: Backup - Attachment



Satellite Attachment Mechanism 2

Helmholtz Cage Testing Structure: Calculations - Line Resistive Torque

τ_{Line} = Resistive Torque from the line
τ_{Sat} = Torque from satellite = 5_E^{-6} Nm
L = length of line = 25 cm
(~ half of the cage height)
J = polar moment of inertia
G = modulus of rigidity
θ = angular deflection = 360°
(requirement from customer)
r = cross-sectional radius of the line between 0.15 mm and 0.4 mm

$\tau_{Line} = J*G*\theta*L^{-1}$

$J = 0.5*\pi*r^4$

$\tau_{Line} = 0.5*\pi* r^4 *G*\theta*L^{-1}$

$G_{experimental}$ = ???

τ_{Line} = ??? Nm

Helmholtz Cage Testing Structure: Locking Mechanism

Structure can be shortened to move and attach line

Structure can be raised for testing

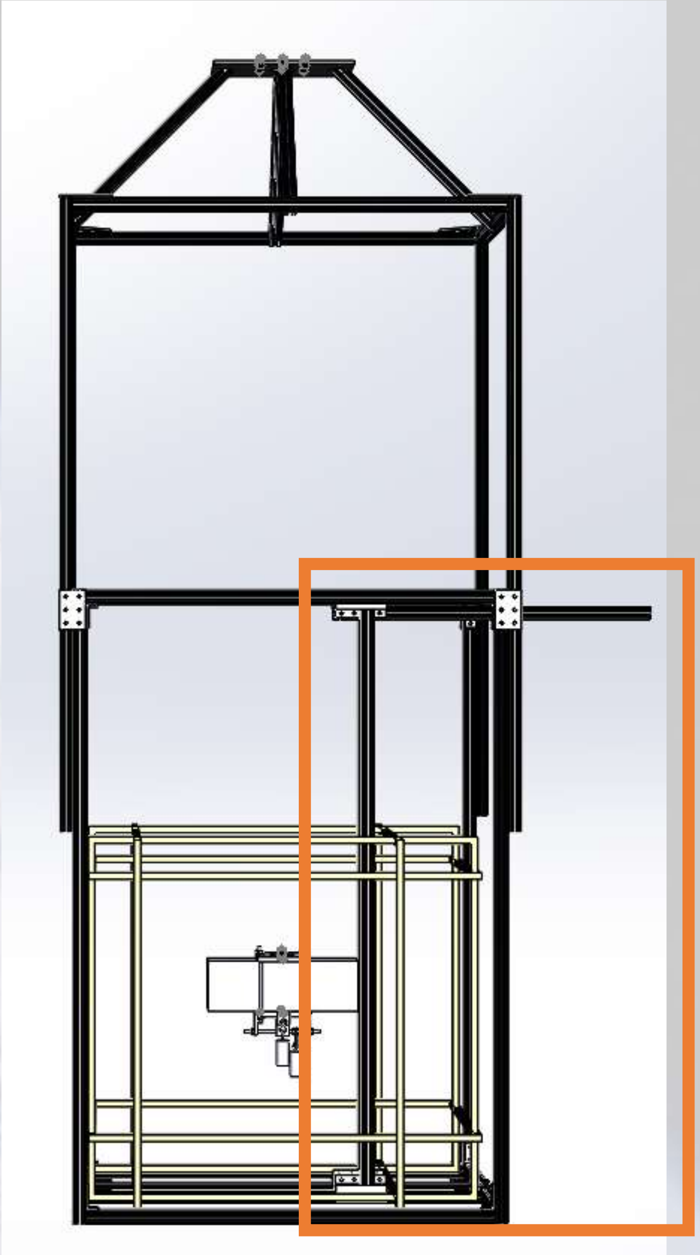
Satellite is attached to line and top of structure

Satellite is left to find center for at least 12 hours

Satellite is rotated to 360 degrees and locked in place

Satellite is released, time to reach 360 degrees is timed

Test Is repeated with magnetorquers activated



Helmholtz Hanging Structure Budget

Item	Manufacturer	Part #	Quantity	Item Price	Revisions	Item Total
1010 extruded aluminum	8020.net	1010	960 inches	0.23/inch	1	220.8
4118 10 series 3 hole joining strip	8020.net	4118	8	4.30/unit	1	$34.40
3321 bolt assembly for joining strip	8020.net	3321	24	0.50/unit	1	$12.00
99553A148 point set screws	mcmaster.com	99553A148	2 packs of 10	4.46/pack	1	$8.92
90670A029 aluminum hex nuts	mcmaster.com	90670A029	4 packs of 100	7.20/pack	1	$28.80
40-6831 40 series 3 slot mount	8020.net	40-6831	4	74.70/unit	1	$298.80
3625 bearing pad screw	8020.net	3625	48	0.12/unit	1	$5.76
4152 10 series 7 hole angle plate	8020.net	4152	4	7.65/unit	1	$30.60
3321 bolt assembly for angle plates	8020.net	3321	28	0.50/unit	1	$14.00
4176 10 series 3 hole inside corner bracket	8020.net	4176	16	3.85/unit	1	$61.60
3393 bolt assembly for corner brackets	8020.net	3393	48	0.40/unit	1	$19.20
4166 10 series 6 hole flat plate bracket	8020.net	4166	4	5.40/unit	1	$21.60
3321 bolt assembly for flat plates	8020.net	3321	24	0.50/unit	1	$12.00
92313A106 cup point set screws	mcmaster.com	92313A106	1 pack of 25	3.45/pack	1	$3.45
9457A510 hex nuts	mcmaster.com	9457A510	1 pack of 5	7.17/pack	1	$7.17
1/4" Aluminum Plate	grainger.com		4 square feet	37.80/sqft	1	151.2
Line			20 inches	0.0023/ft	1	$20.00
					Total:	$950.30

Sun Sensor Calibration Table Budget

Item	*Manufacturer*	*Part #*	*Quantity*	*Item Price*	*Revisions*	*Item Total*
Aluminum1	mcmaster		1	$100	1	$100.00
Aluminum2	mcmaster		1			
Aluminum3	mcmaster		2			
Ball bearing	mcmaster		1	$30	1	$30.00
Rotary magnetic encoder	allied electric		1	$80	1	$80.00
DC motor	sparkfun		1	$70	1	$70.00
Analog to digital converter	arduino		1	$30	1	$30.00
LCD display			1	$30	1	$30.00
Anodized coating			1	$300	1	$300.00
Gear 1	mcmaster		1			
Gear 2	mcmaster		1			
Screws	mcmaster		various			
Spacers	mcmaster		1			
					Total:	$640.00

Interface Board Budget

Item	Manufacturer	Part #	Quantity	Item Price	Revisions	Item Total
Master Microcontroller	Microchip	PIC18F67J94	1	$4.44	5	$22.20
Slave Microcontroller	Microchip	PIC16F1847	10	$1.65	5	$82.50
USB to UART	FTDI	FT232RL	1	$4.50	5	$22.50
Current Sensor	Allegro	ACS712	2	$4.82	5	$48.20
Linear Voltage Regulator	STMicroelectronics	LD1117S33CTR	2	$0.51	5	$5.10
Dual P-Channel MOSFET	ON Semiconductor	NTJD4152P	1	$0.43	5	$2.15
Push Button	C&K Components	PTS525 SM15 SMTR2 LFS	11	$0.60	5	$33.00
Test Point	Keystone	5006	30	$0.35	5	$52.50
Banana Plug - Female	Cinch Connectivity Solutions Johnson	105-0753-001	2	$0.81	5	$8.10
Bridge Diode	Fairchild Semiconductor	MDB6S	1	$0.51	5	$2.55
USB-B Connector	On Shore Technology Inc.	USB-B1HSB6	1	$0.58	5	$2.90
ADCS Connector	Samtec	QFS-026-01-L-D-RA-PC4		$0.00	5	
PCB - 4 layer full spec, student price, no minimum order	Advanced Circuits	TBD	1	$66.00	5	$330.00
FTDI Cable - Wires	FTDI	TTL-232RG-VREG3V3-WE	1	$24.64	1	$24.64
FTDI Cable - Header	FTDI	TTL-232R-3V3	1	$20.00	1	$20.00
					Total:	$656.34