Mapping **A**rchitecture **C**oncept for **U**niversal **L**anding **A**utomation

MACULA

CRITICAL DESIGN REVIEW

Customer: Jeffrey Thayer & Brian Argrow, University of Colorado Boulder AES

Faculty Advisor: Jay McMahon

Team Members:

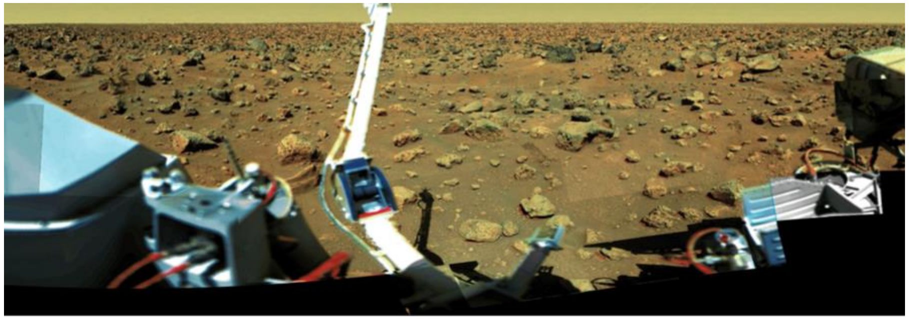
Trevor Arrasmith, Brett Bender, Chris Brown, Nick Dawson, David Emmert,
Bryce Garby, Russell Gleason, Matthew Hurst, Jared Levin, Ansel Rothstein-Dowden

Agenda

Project Purpose / Objectives	Brett
Design Solution	Brett
Critical Project Elements	Russell
Design Requirements & Satisfaction	Trevor, Russell
Project Risks	David
Verification & Validation	Jared
Project Planning	David

PROJECT PURPOSE AND OBJECTIVES

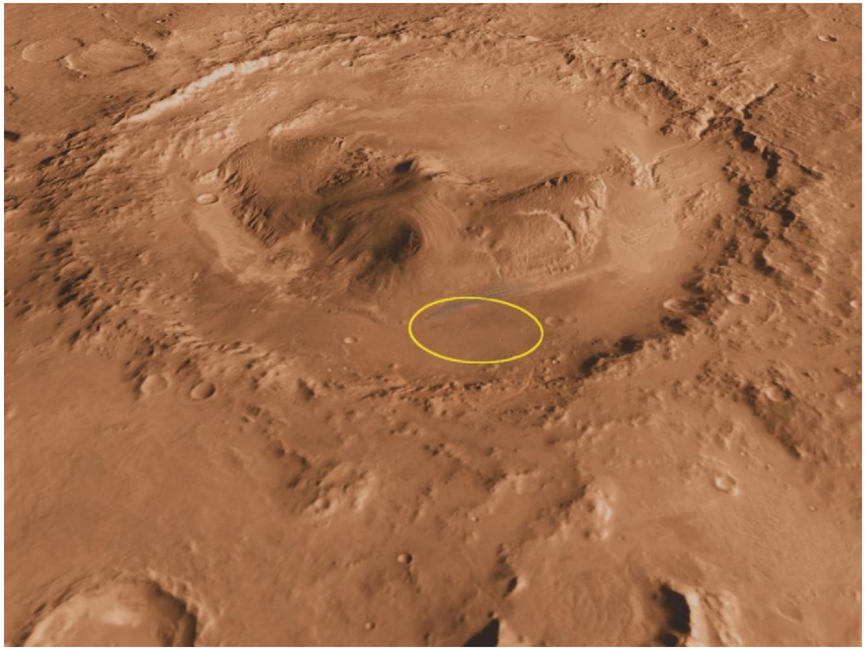
Motivation



Rocks on the Martian surface

http://geology.isu.edu/wapi/Geo_Pgt/Mod09_Mars/images/VIEWFRMLANDER2VLFMOS21.gif

Landing zones for spacecraft must be pre-determined as “safe,” and can be far from areas of scientific interest



Curiosity’s error ellipse on Mars (20 km minor, 25 km major axis)

http://www.nasa.gov/images/content/573652main_pia14294-anno-43_946-710.jpg

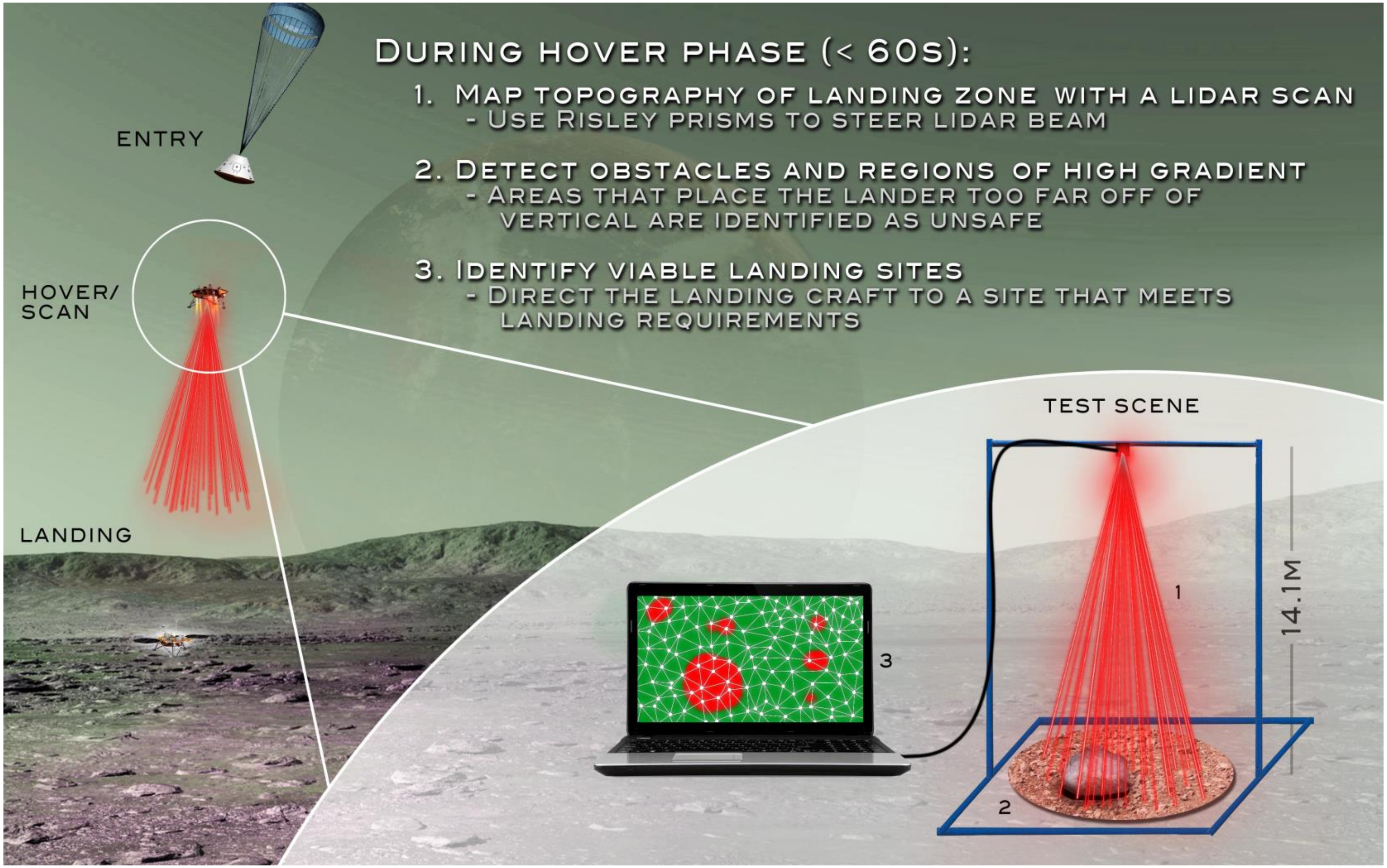
Project Objectives

Design, **manufacture**, and **test** a **proof-of-concept** light detection and ranging (lidar) **scanning system** for a landing spacecraft

Success Levels:

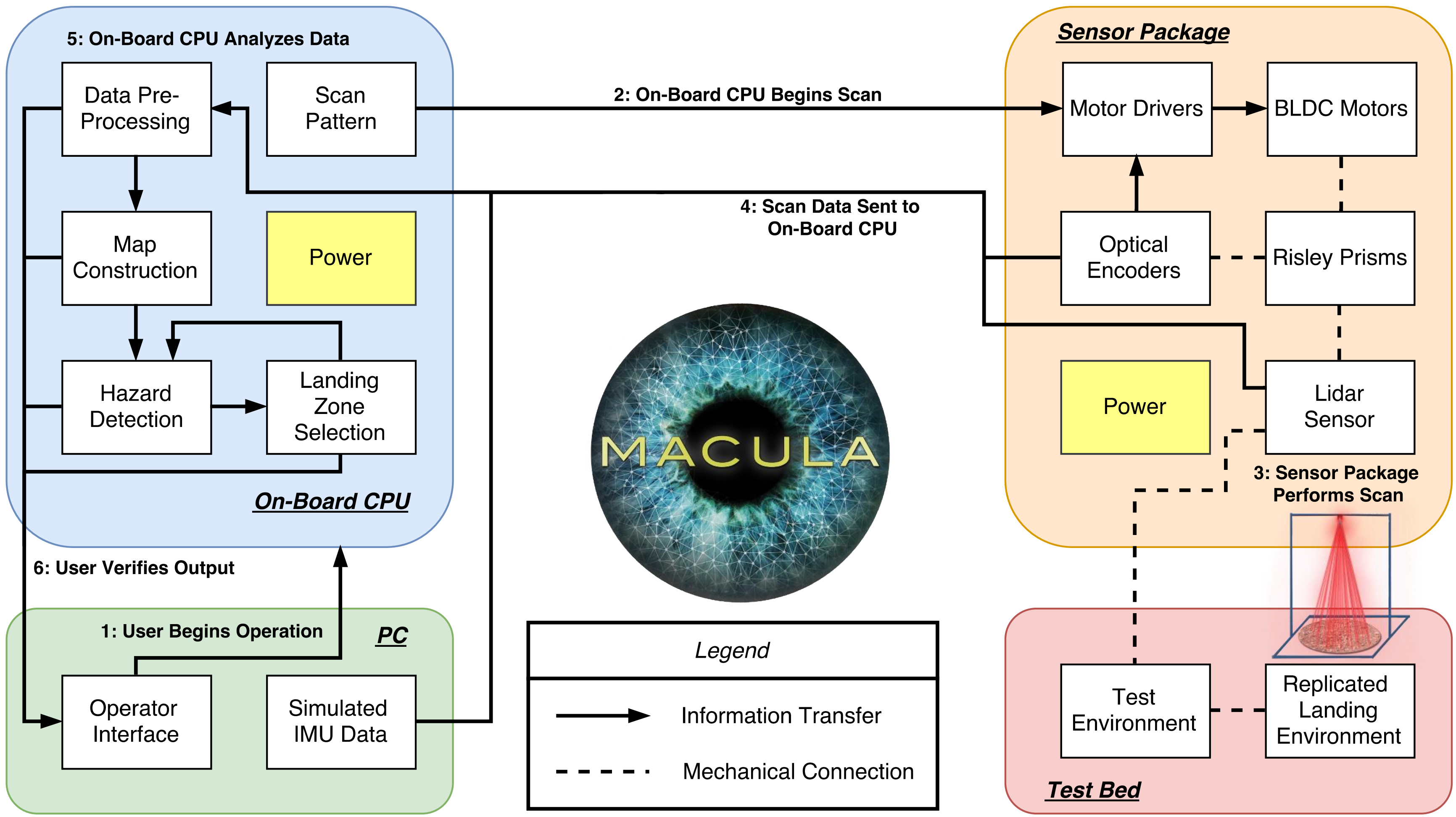
1. Lidar sensor and scanning mechanism, mounted on a stationary platform, shall **record correlated range and attitude measurements** at a 0.1 m spatial resolution from a nadir distance of 14.1 m with a maximum 20° off nadir
2. System shall scan a known test scene and **project measurements into a 3D point cloud**
3. System shall scan a landing-zone mockup and **analyze the 3D point cloud for hazards**
4. System shall **select a safe landing zone**; if no safe landing zone is found, hazard definition will be loosened until a landing zone is found

Concept of Operations

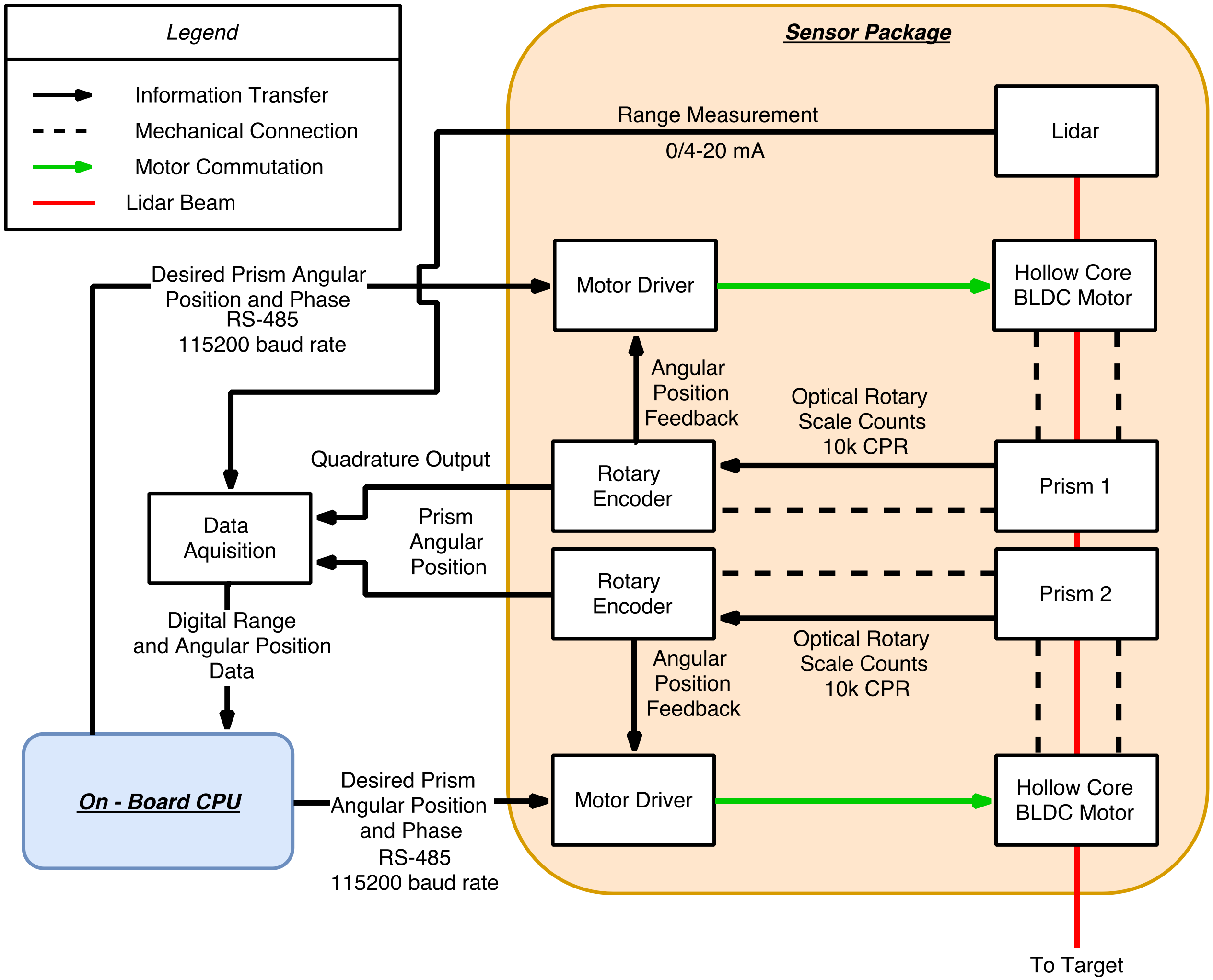


DESIGN SOLUTION

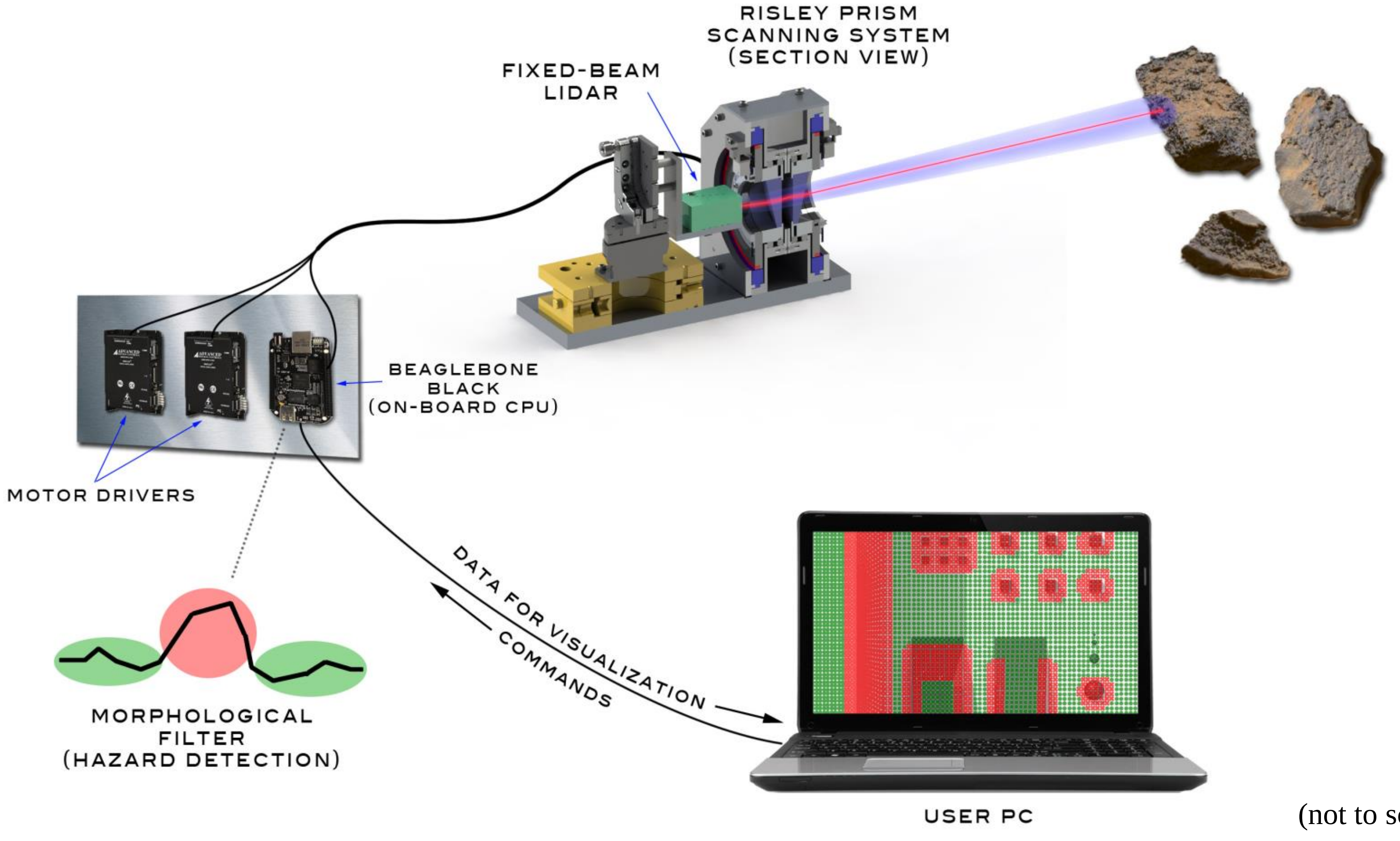
Functional Block Diagram



Hardware Architecture Diagram

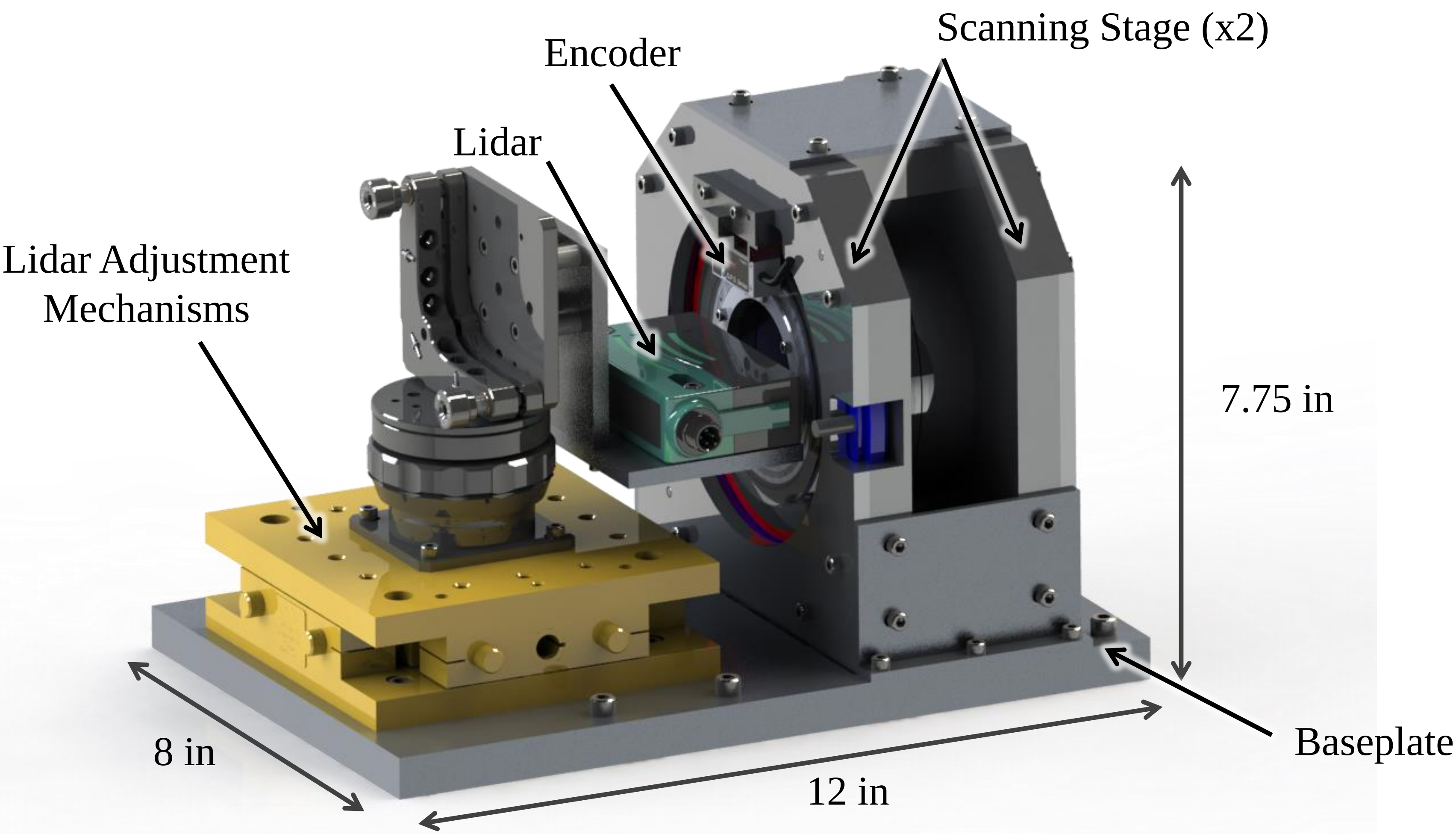


Final Design Overview



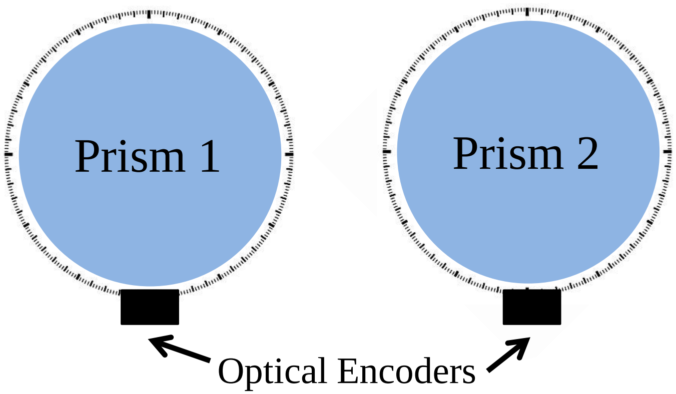
(not to scale)

Full Scanning System

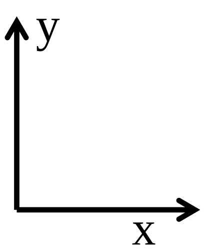


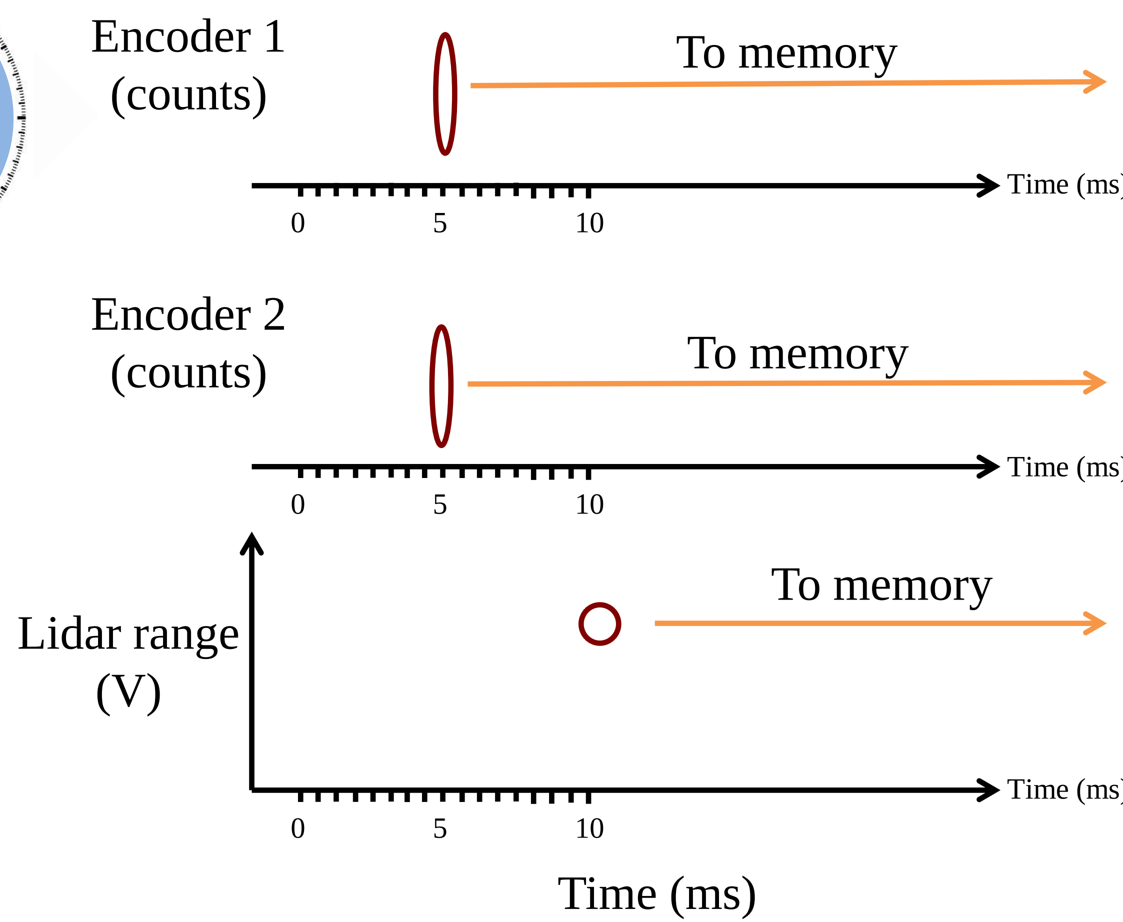
Timing

Risley Prisms (beam view)

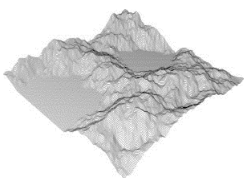


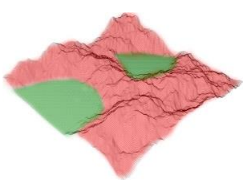
Lidar ground track





Software





Sensor Data

↓

Coordinate Transformations

↓

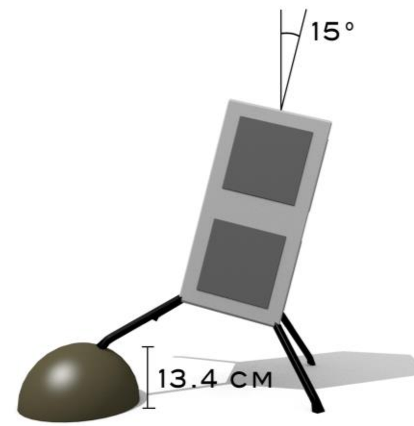
Hazard Detection

↓

Landing Zone Selection

At each point:

- Find neighboring points within lander footprint
- ↓
- Find maximum and minimum heights in subset
- ↓
- If max. minus min. is too large, the point is hazardous



Critical Project Elements

Critical Project Elements

1. Optics (direct laser pulse and obtain range measurement)
   – Lidar
   – Risley Prisms
2. Risley Prism Control (achieve desired scan pattern)
   – Scan Pattern
   – Motors
   – Motor Drivers
   – Encoders
3. Embedded System (sensor communication)
   – Microcontroller + Motor Drivers/Encoders/Lidar

Design Requirements and their Satisfaction

Functional Requirements

FR 1: The system shall analyze a potential landing zone for a 12U cubesat.

FR 2: The on-board processor (OBP) shall receive commands and data from a user-operated PC (UPC).

FR 3: The OBP shall command the sensor package (SP).

FR 4: The SP shall use fixed-beam lidar sensor to obtain range measurements.

FR 5: The SP shall have control over the direction of the lidar beam direction using two Risley prisms.

FR 6: The OBP shall receive data from the SP.

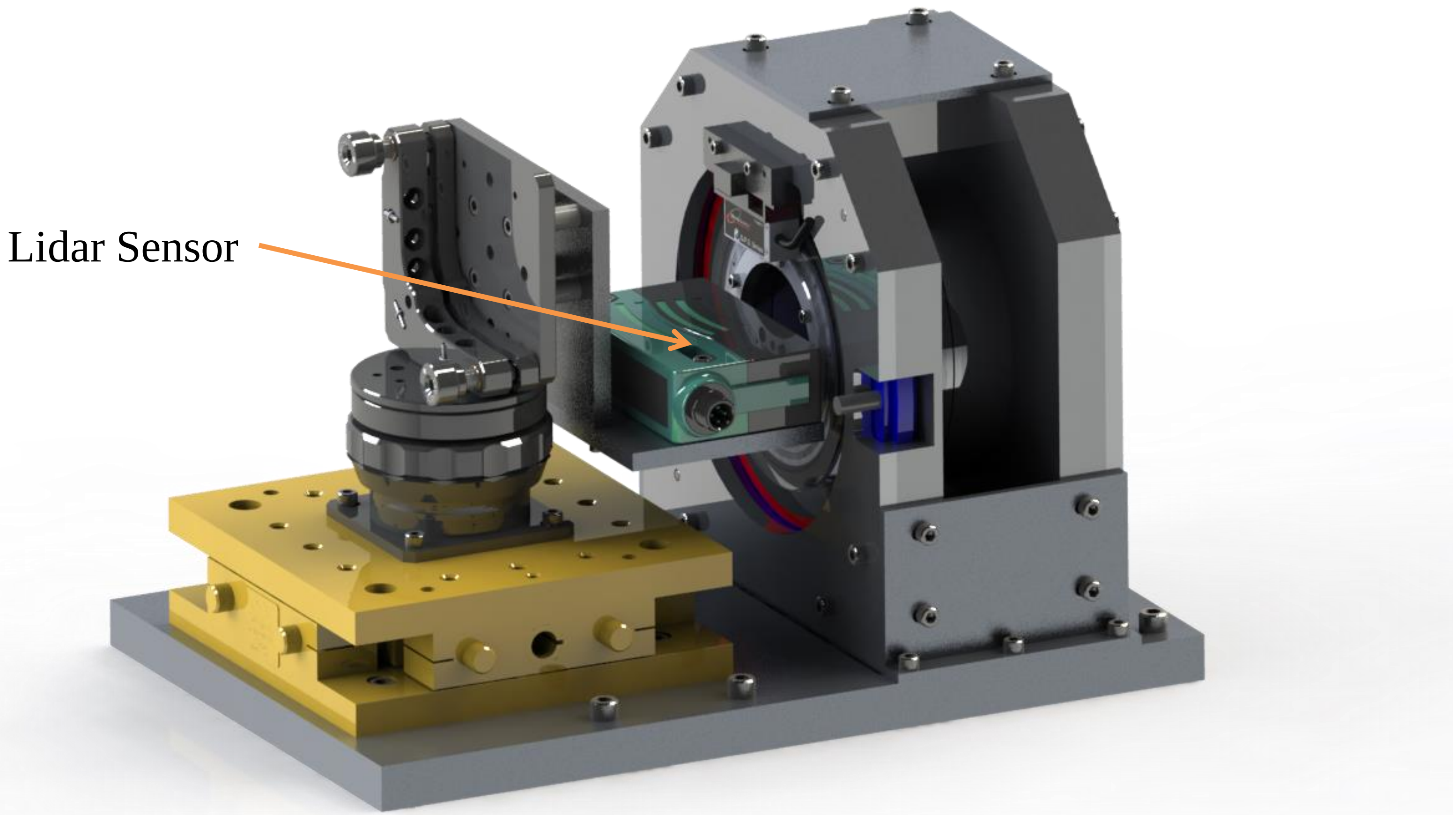
FR 7: The OBP shall project the SP data into a 3D point cloud.

FR 8: The OBP shall analyze the 3D point cloud to identify hazardous locations.

FR 9: The OBP shall select an acceptable landing site.

FR 10: The OBP shall generate output readable by the UPC.

DRs: Lidar Sensor



DRs: Lidar Sensor

<u>Pepperl+Fuchs VDM28</u>

- **FR 4:** The SP shall use fixed-beam lidar sensor to obtain range measurements.

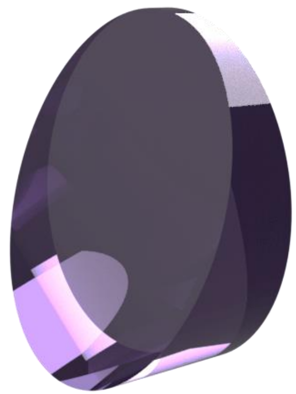
	Required	**Pepperl+Fuchs VDM28**
Range	12 m - 15 m	0.2 m - 15 m
Range Error	<0.05 m	0.025 m
Cross Range Error	<0.045 m	0.0080 m

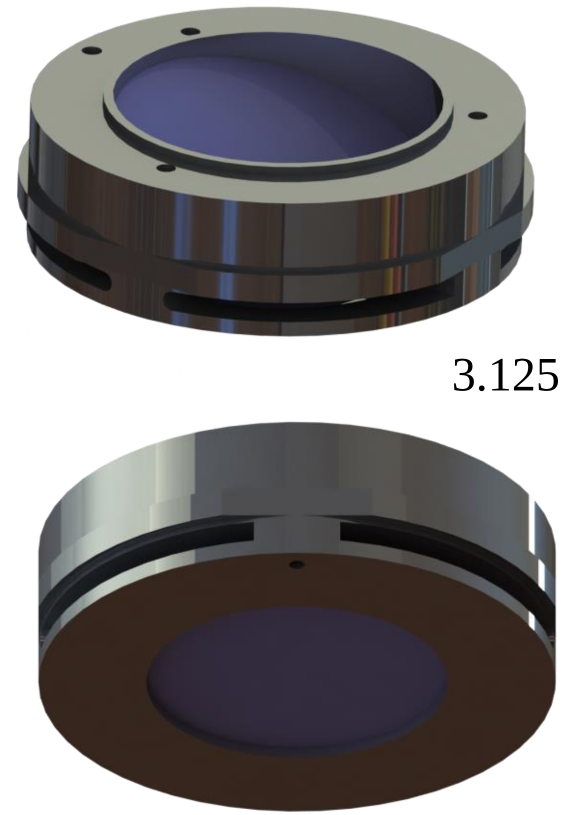
Cost: ~$500 (donated)
Sampling Frequency: 100 Hz
Wavelength: 660 nm

DRs: Risley Prisms

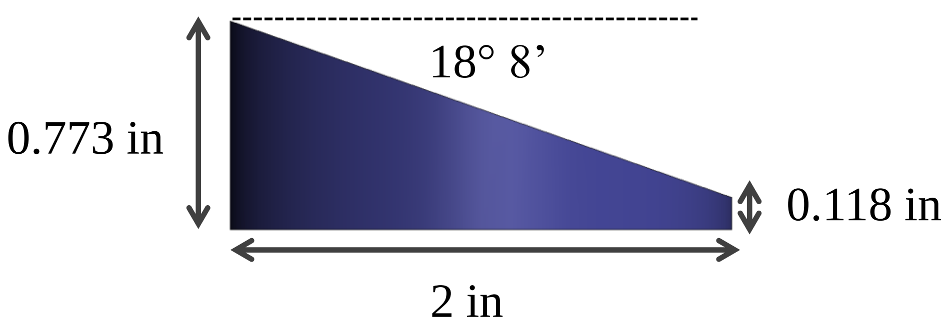
FR 5: The SP shall have control over the direction of the lidar beam direction using two Risley prisms.

DR 5.1.1: 20° scan angle, **DR 5.2:** Individually controlled, **DR 5.4:** Shall not inhibit lidar sensor

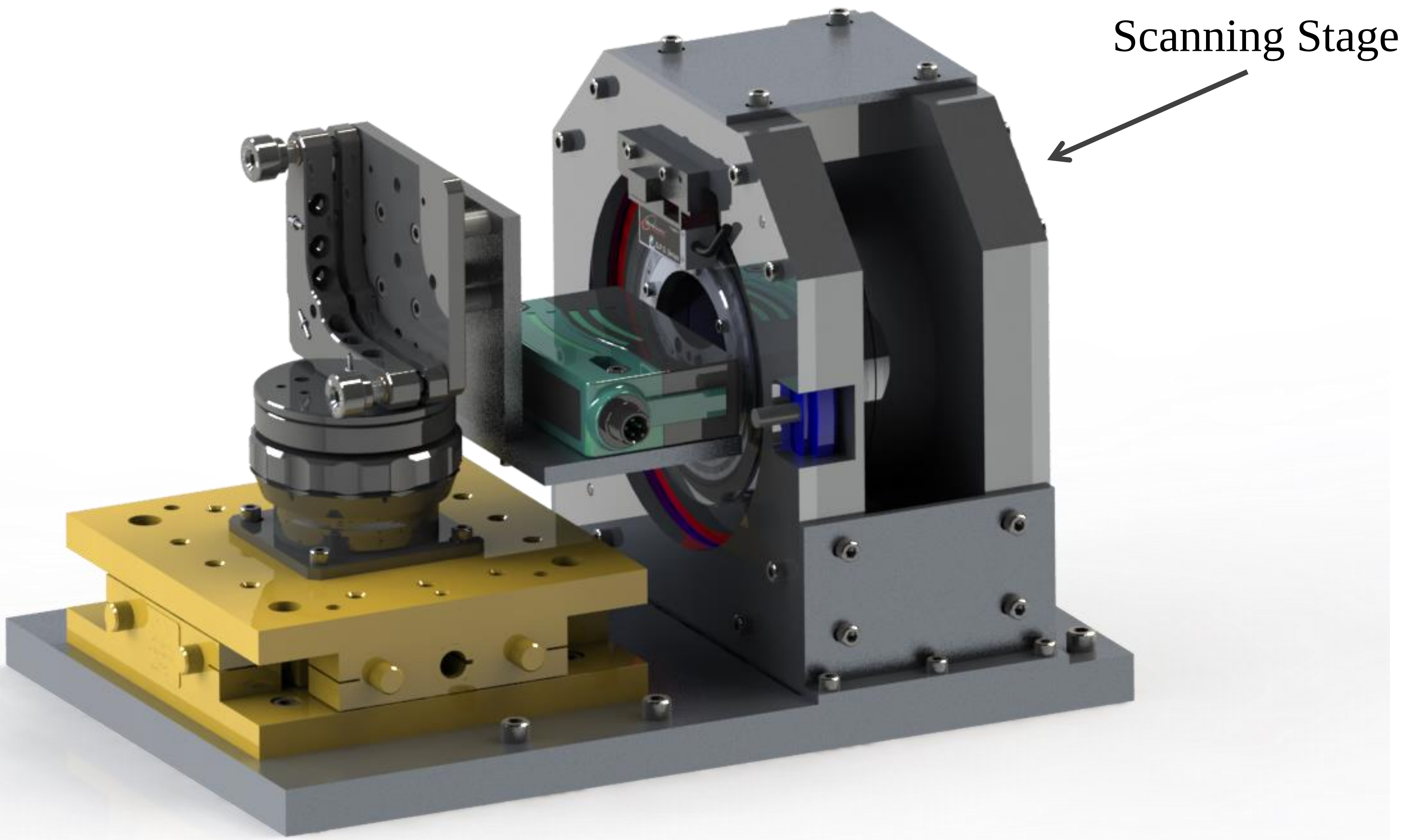




3.125 in (O.D.)



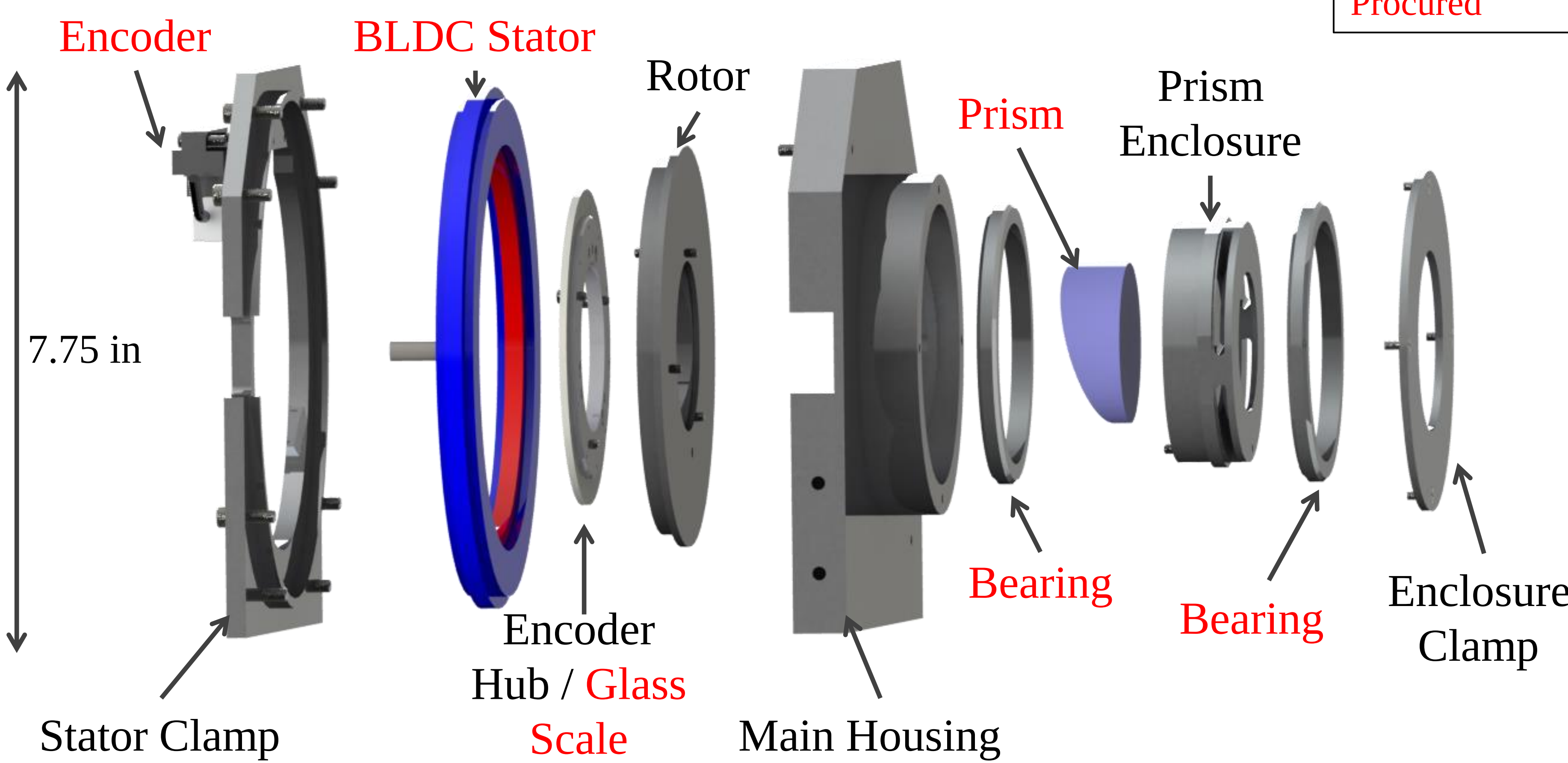
DRs: Risley Prisms



DRs: Risley Prisms

Scanning Stage Exploded:

Manufactured
Procured

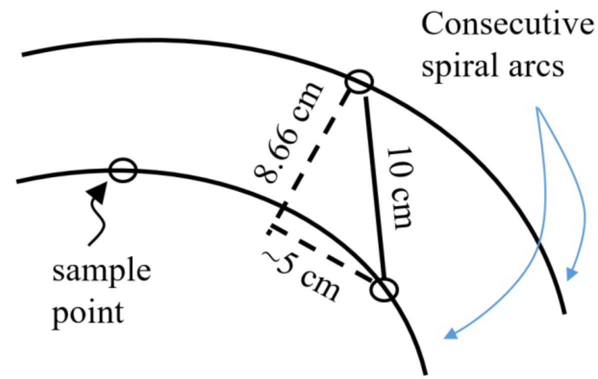


DRs: Scan Pattern

DR 1.1-1.4: 10 cm spatial resolution at 14.1 m nadir range with 20° maximum scan angle

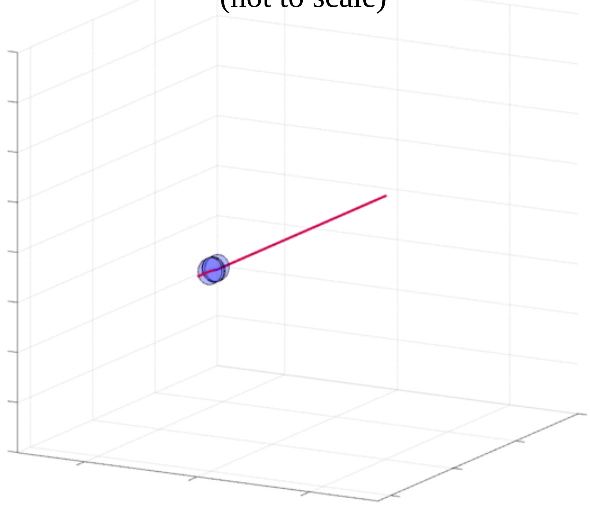
⇓

Spiral with 59.2 revolutions spaced 8.66 cm apart



Animation of Scan with Risley Prisms

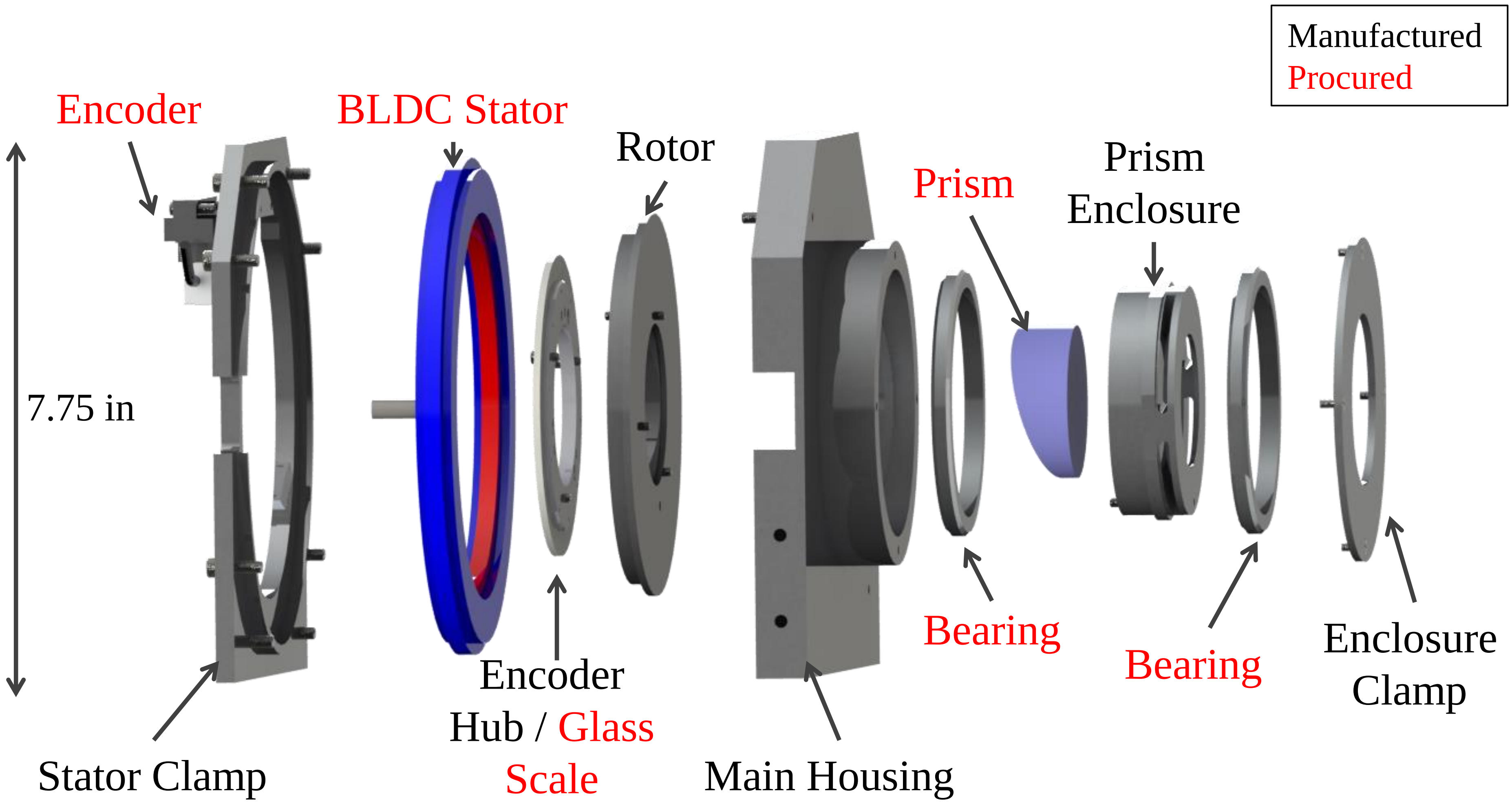
(not to scale)



What will this design choice mean for the Risley prism actuation system?

	Time Test	Resolution Test
Max Speed [rad/s]	8.46	0.55
Min Speed [rad/s]	7.34	0.48
Max Acceleration [rad/s^2]	14.36	0.05

DRs: Motors



Manufactured
Procured
Encoder
BLDC Stator
Rotor
Prism
Prism Enclosure
7.75 in
Bearing
Bearing
Enclosure Clamp
Stator Clamp
Encoder Hub / Glass Scale
Main Housing

DRs: Motors

DR 5.2.1: 15 rad/s^2, **DR 5.2.2**: 0.45 rad/s – 10 rad/s

Inertia of rotating components: 9.5x10^{-4} kg m^2

Direct Drive:

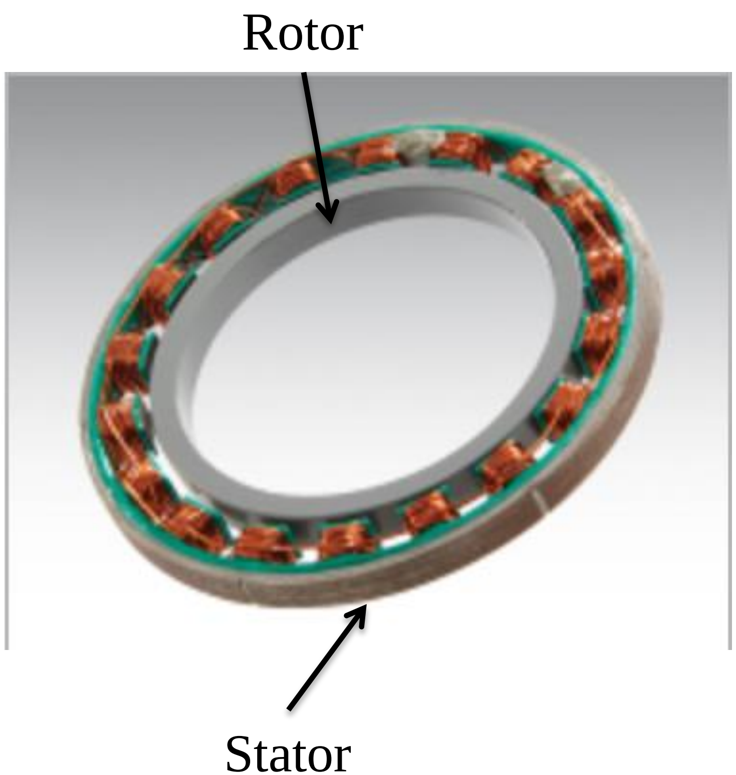
- Most mechanically simple solution that satisfies requirements

Brushless DC (BLDC) Motor:

- Large hollow core required for optics
- Fine continuous control of pointing or speed

ULT-165-A-12-A-x-00x:

- Up to 5000 RPM (~523 rad/s)
- Max continuous torque of 1.255 Nm (~1200 rad/s^2)
- 4.4 in. rotor inner diameter



DRs: Motor Drivers

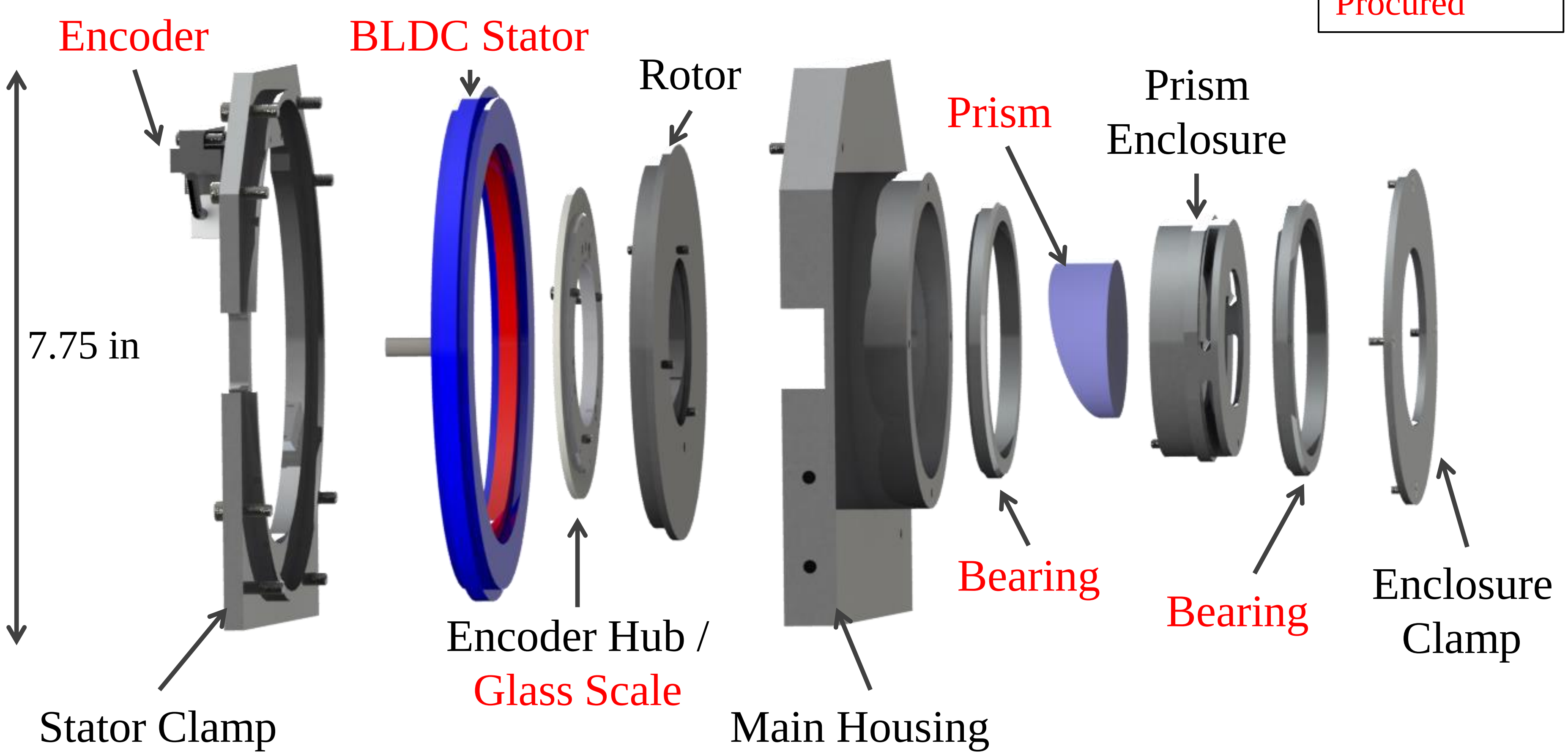
Advanced Motion Controls DPRALTE (~$600 each)

DR 3.3: The OBP shall send commands to the motor drivers.

	Design Req.	DPRALTE
Commanding	Shall be commanded from OBP at least once every 10 ms	RS485 and step input
Motor Rates	4.3 – 96 RPM (0.45 – 10 rad/s)	4 – 120 RPM (0.42 – 12.6 rad/s)

DRs: Angular Position Sensor

Manufactured
Procured



Celera Motion OPS-SM-40 (~$600 each)

Prism orientation measurements are required for motor control and for beam attitude knowledge.

	Design Req.	OPS-SM-40
Angular Uncertainty	Stackup	± 0.009°
Measurement Time	≤ 1 μs	5 ns

Manufactured
Procured

3.937 in (O.D.)
2.125 in (I.D.)
0.188 in thick

DRs: Microcontroller (OBP)

BeagleBone Black (~$55)

FR 2: The OBP shall receive commands and data from a user-operated PC.

FR 3: The OBP shall command the sensor package.

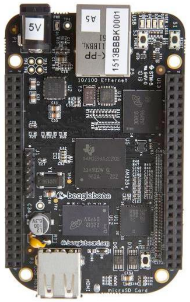
DR 4.6: Lidar range and beam attitude measurements shall be taken within one microsecond.

FR 6: The OBP shall receive data from the sensor package.

FR 7-9: Analyze sensor measurements to determine a safe landing site.

FR 10: The OBP shall generate output readable by the PC.

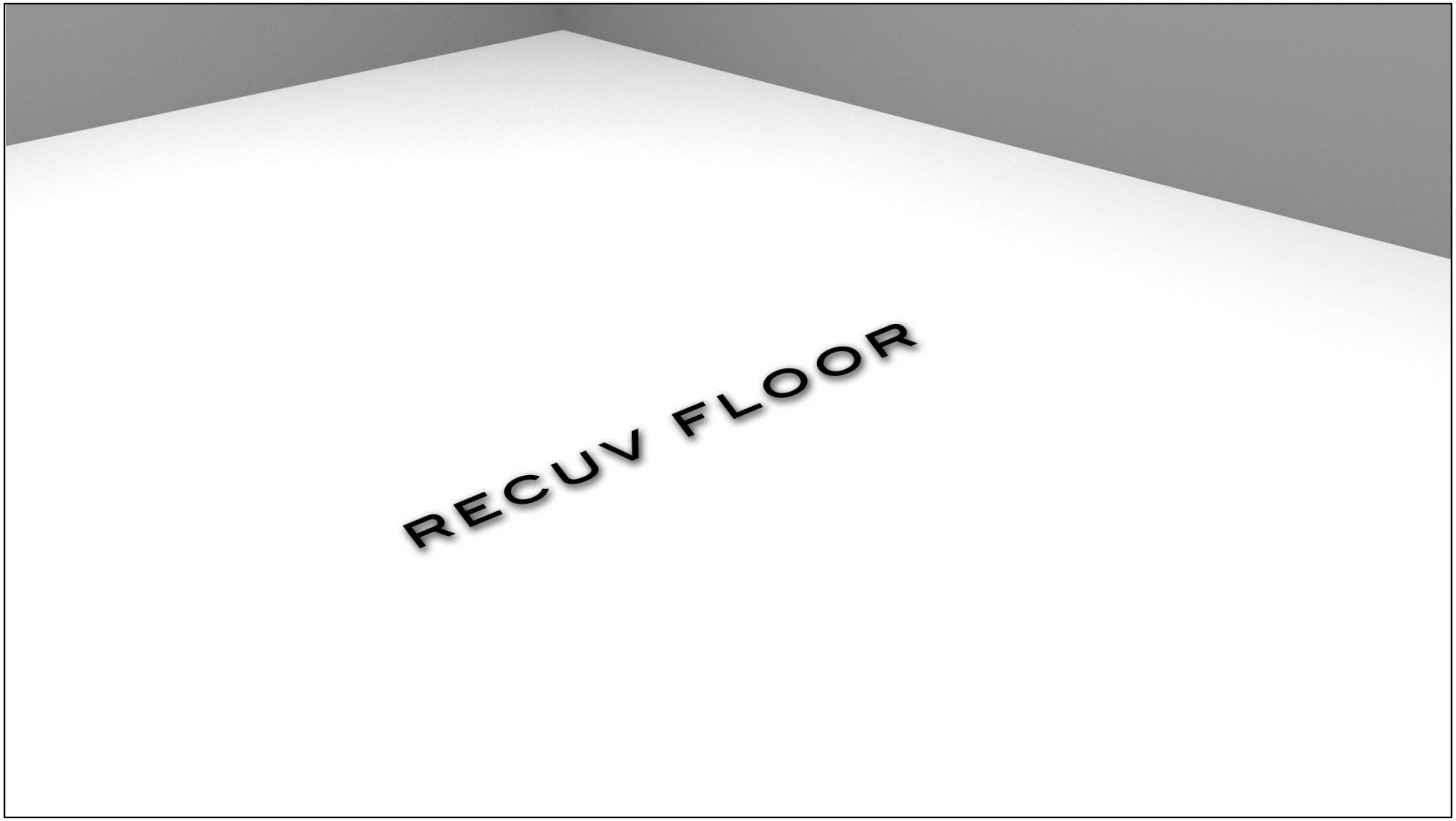
	Design Req.	BeagleBone Black
Communication with PC	Receive commands & data, update status, write results	UART, USB, Ethernet
Communication with sensor package	Command motor drivers	UART←→RS485, GPIO
Measurement time	$\leq 1\ \mu s$	~600 ns (full ADC conversion)
Crunch data	FPU→10 second computation time	~ capable of 1 Gigaflop



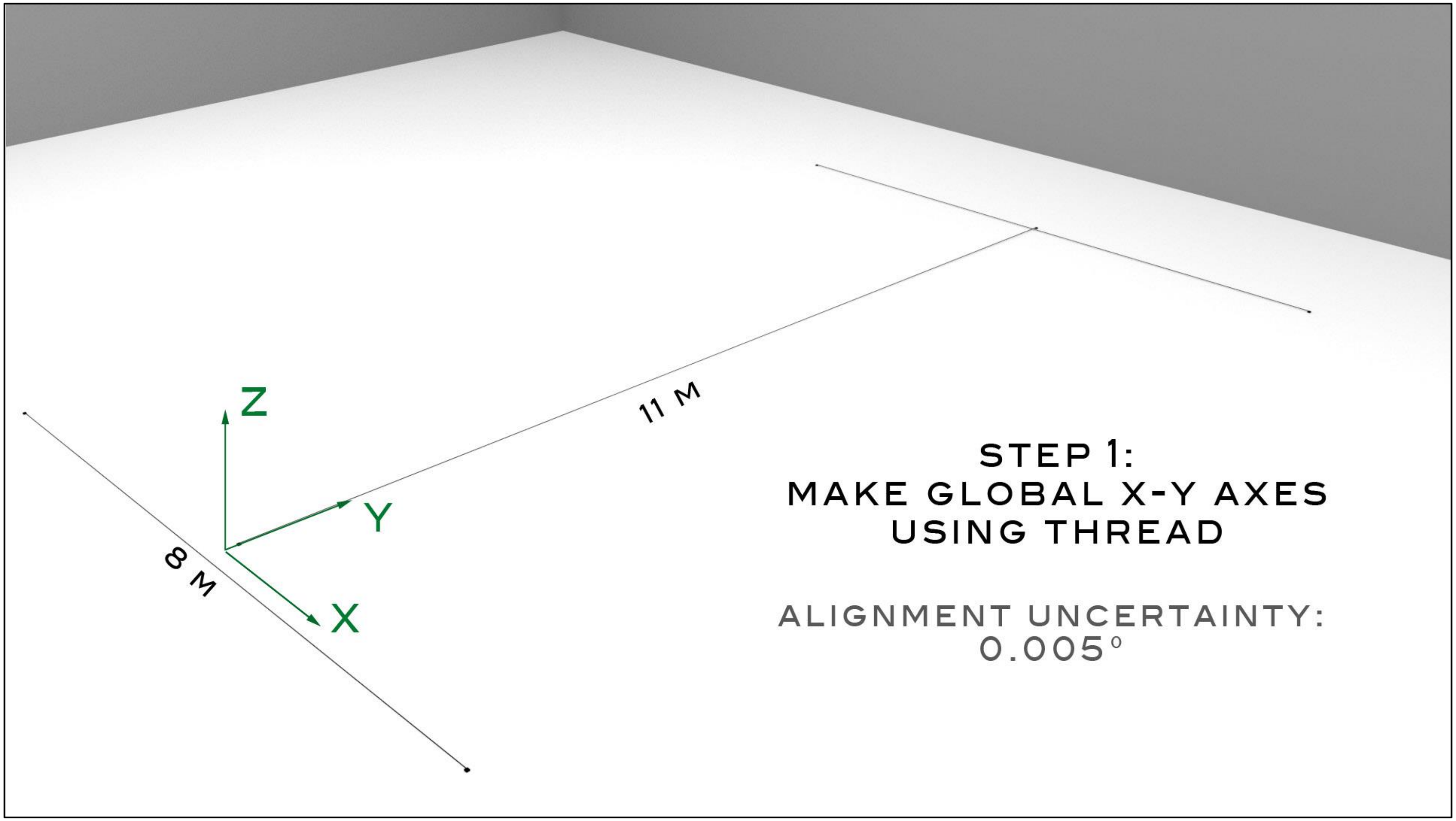
Calibration Plan

- This calibration test plan determines the alignment of the lidar and prisms to within a tolerance that meets our pointing knowledge requirement
    - DR: Error ≤ 5 cm in the plane of the ground
- Most of the error in the beam steering is systematic and can be accounted for in software
- Reassembling the system after calibration introduces uncertainties that will not be calibrated

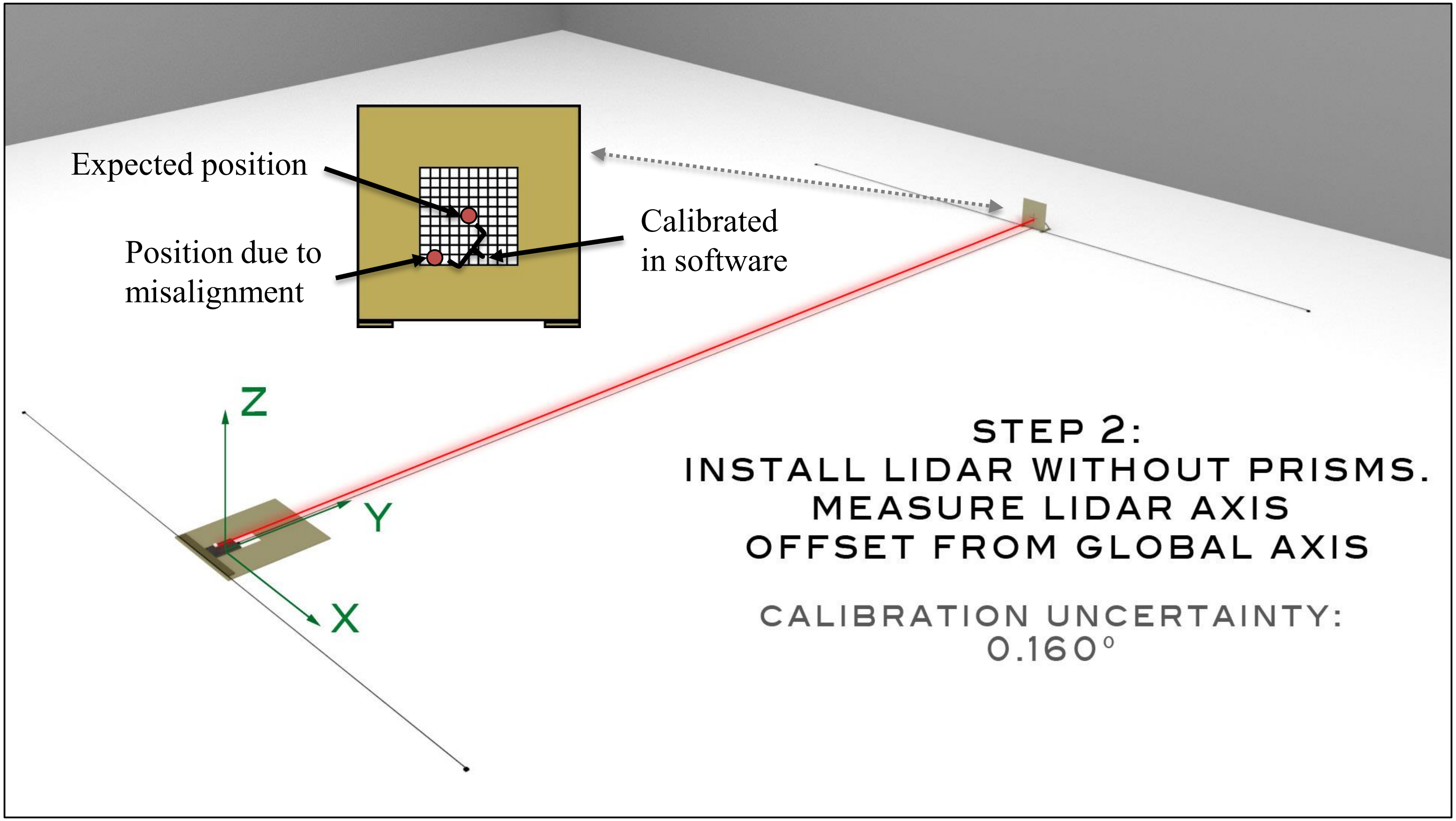
Test Plan: Calibration



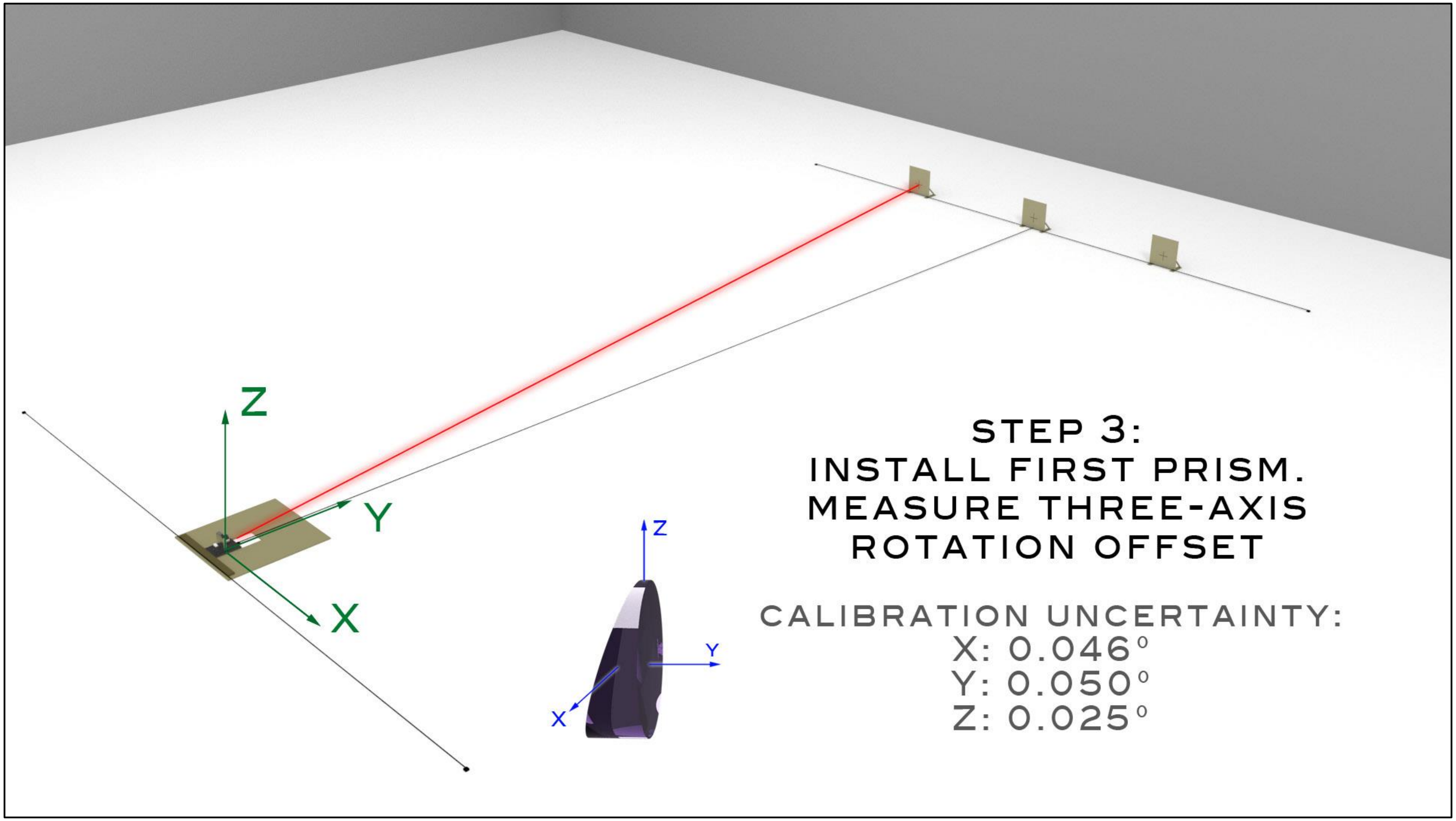
Test Plan: Calibration



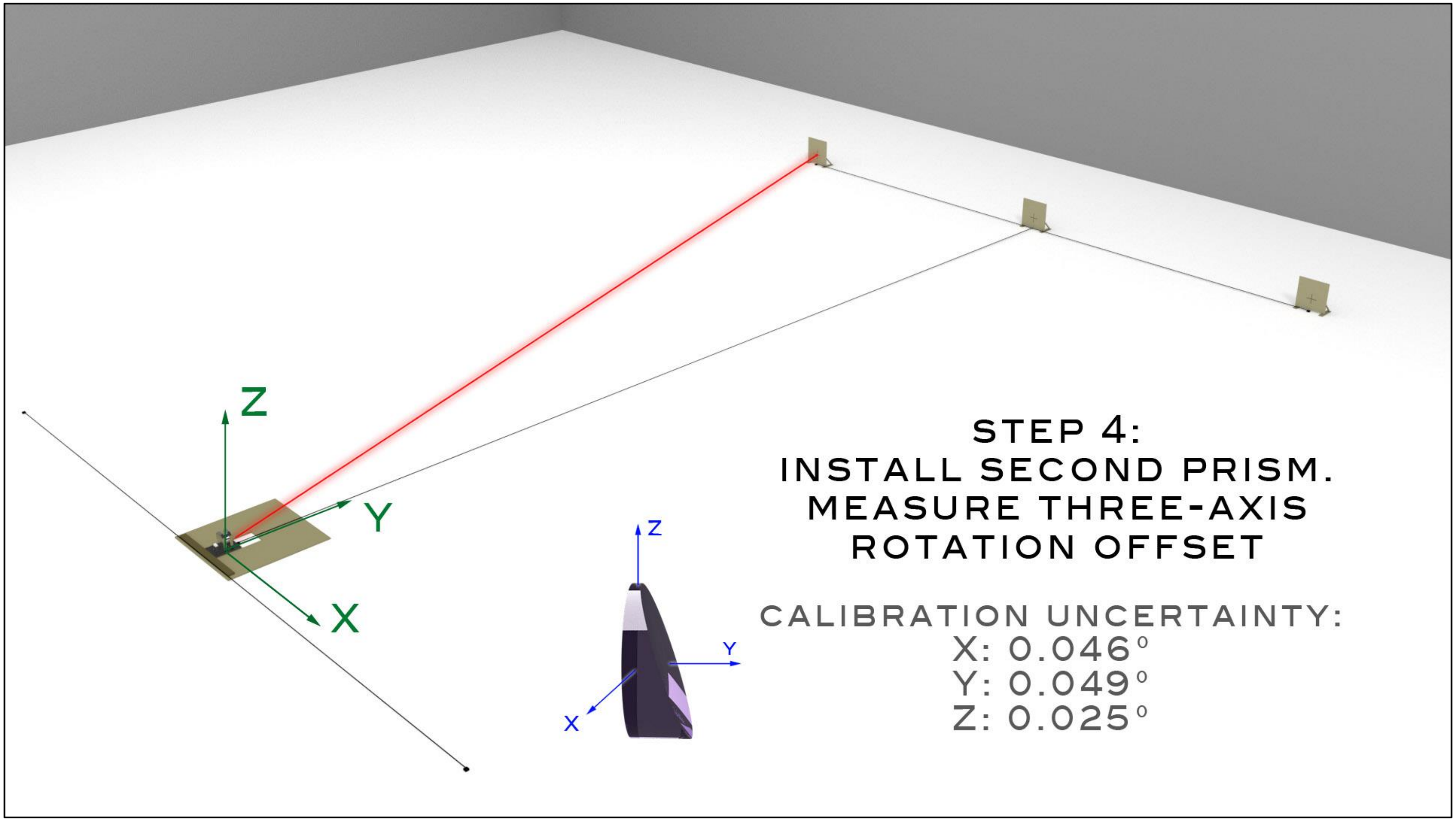
Test Plan: Calibration



Test Plan: Calibration

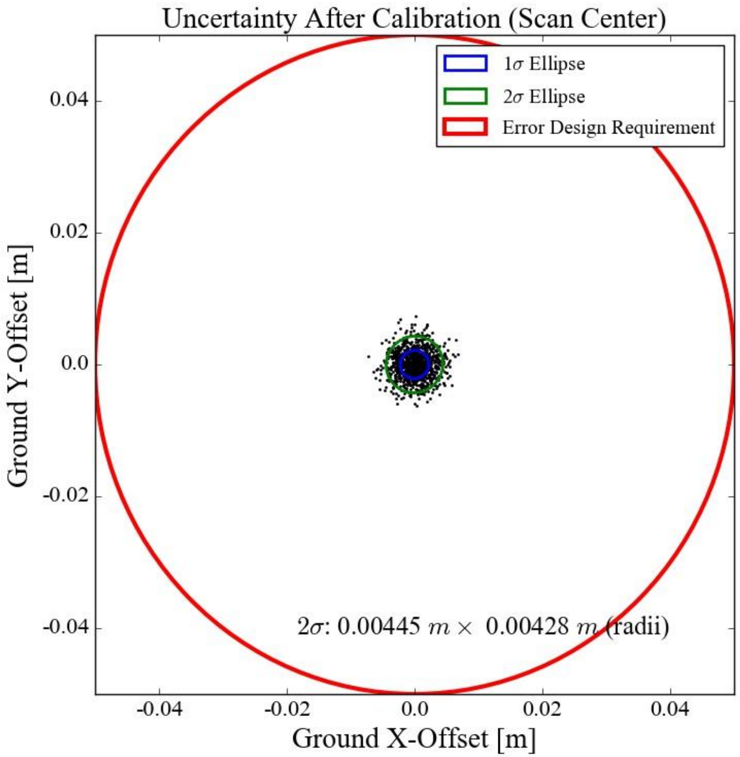


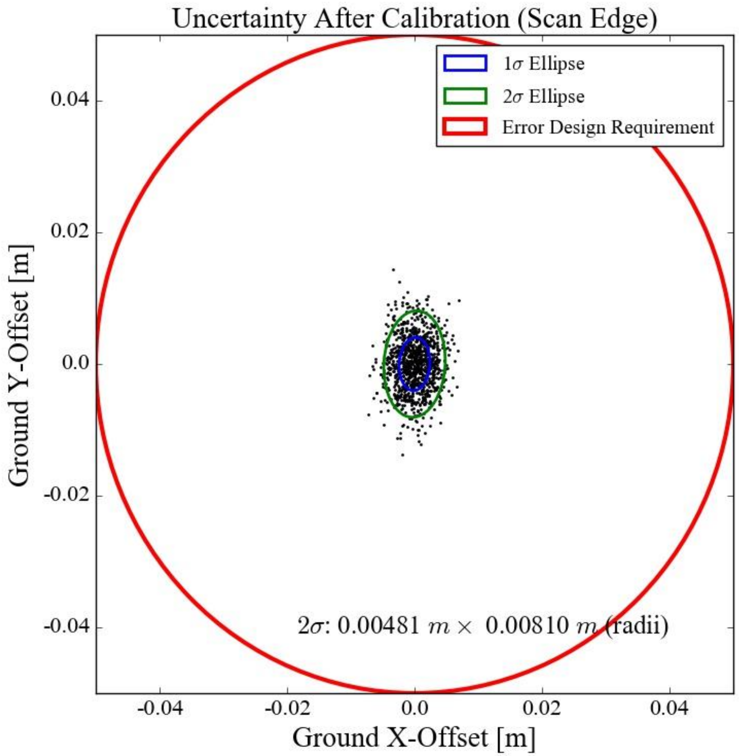
Test Plan: Calibration



Test Plan: Calibration

- This shows that the system does not need to be permanently fixed after our calibration tests





PROJECT RISKS

Risk Summary

R1	**Reflection off of prisms causes false return**
R2	**Encoder mount damage occurs during shipping, glass scale installation, or storage**
R3	**Limited machine shop availability due to schedules and use by other students**
R4	**Risley prism damage occurs during storage or handling**

		Severity				
		1	2	3	4	5
Likelihood	5					
	4		R3			
	3					R1
	2				R2/4	
	1					

Risk Summary

R5	**RECUV test facility unavailable at necessary times and/or necessary durations**
R6	**Delays during manufacturing process**
R7	**Loss of calibration resulting from moving system around and/or adjusting system during testing**

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3			R6/R7		
	2			R5		
	1					

Mitigation

R1	Reflection off of prisms causes false return
	1. Add broadband antireflective coating to prisms (for 400-700 nm wavelength)
	Reduces likelihood of risk
	2. Test using two different lidar sensors (diffuse & specular detectors)
	Reduces likelihood of risk

Type of Risk

- ☐ Budget
- ☑ Technical
- ☐ Safety
- ☐ Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3					X
	2					1/2
	1					

Mitigation

R6	Delays during manufacturing process
	1. Utilize full extent of machining resources available, included multiple shops (Aero, ITLL) and full time employees who will machine parts
	Reduces likelihood of risk
	2. Manufacture parts in parallel using all available team members
	Reduces likelihood of risk
	3. Purchase extra stock that can be used if parts need to be remade
	Stock materials can be bought with 20% budget margin
	Reduces severity of risk

Type of Risk

- ☑ Budget
- ☐ Technical
- ☐ Safety
- ☑ Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3		3	X		
	2		1/2/3	1/2		
	1					

Mitigation

R7	**Loss of calibration resulting from moving system around and/or adjusting system during testing**
	1. Place covers over adjustment knobs to prevent accidental adjustments
	Reduces likelihood of risk
	2. Include margin time during testing to allow for calibration
	Reduces severity of risk

Type of Risk

- ☐ Budget
- ☑ Technical
- ☐ Safety
- ☑ Schedule

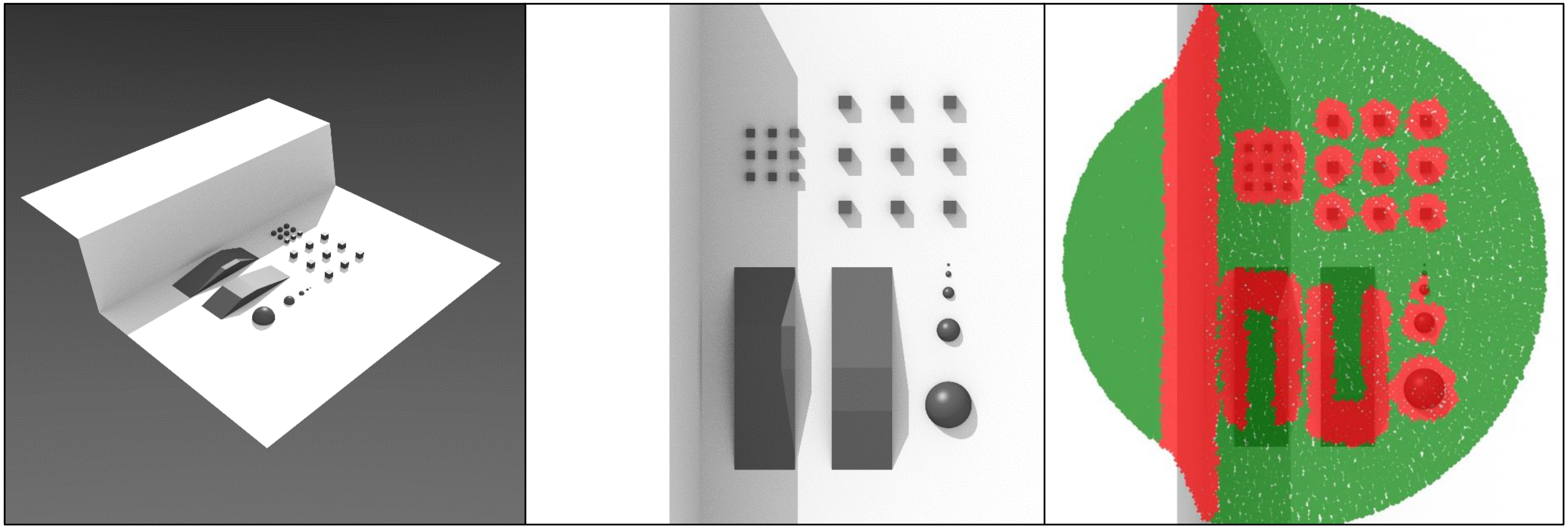
		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3		2	X		
	2		1/2	1		
	1					

VERIFICATION AND VALIDATION

Predicted Performance

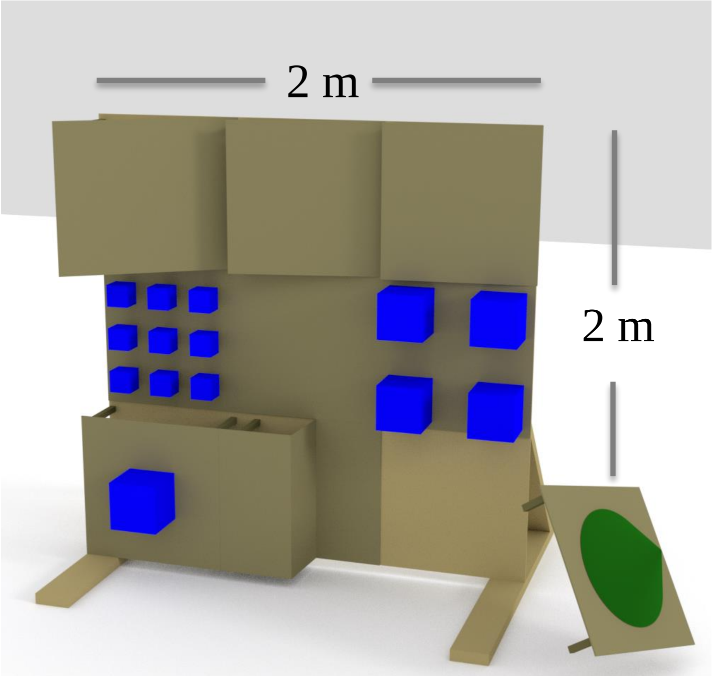
- The lidar-generated point cloud will be compared against the physical dimensions of the test bed
- Hazard detection results will be compared against simulated scans

Hazard detection with all uncertainties applied



Test Setup

- Construct a landing zone mockup with known dimensions
- Nine modular test panels
- Characterization tests
  - Flat wall
  - Safe and hazardous slopes
  - Safe and hazardous cubes
  - Cliff
  - Cone
  - Rocky shapes
- Can measure dimensions manually or with handheld 3D scanner
  - Compare lidar-generated point cloud to point cloud made from measurements to determine accuracy

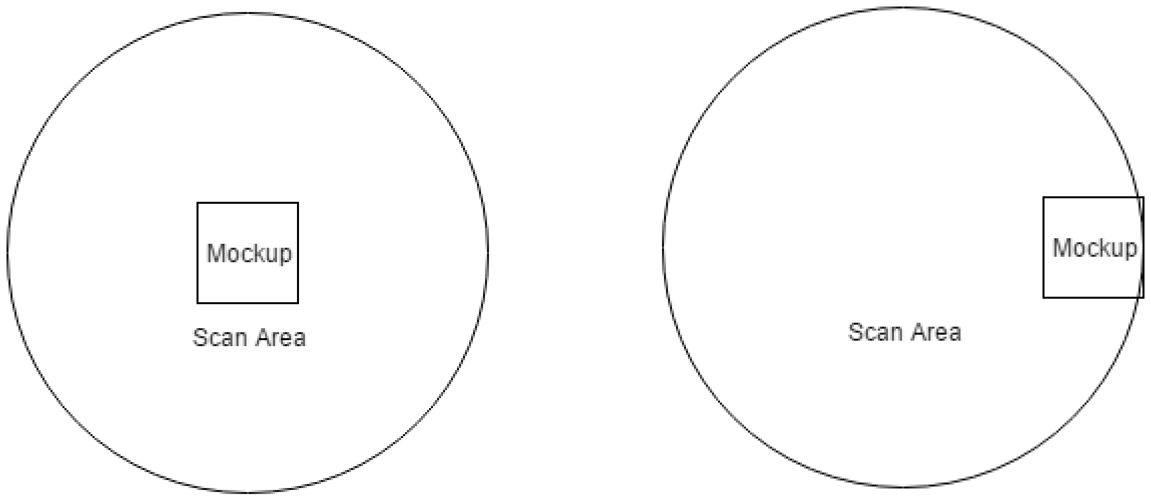


Test Process

- Two system tests must be conducted to meet requirements
  - Resolution requirement
    - 12.5 minutes
    - Must accurately identify hazards
  - Time requirement
    - 50 seconds for complete scan
    - 59.2 spirals

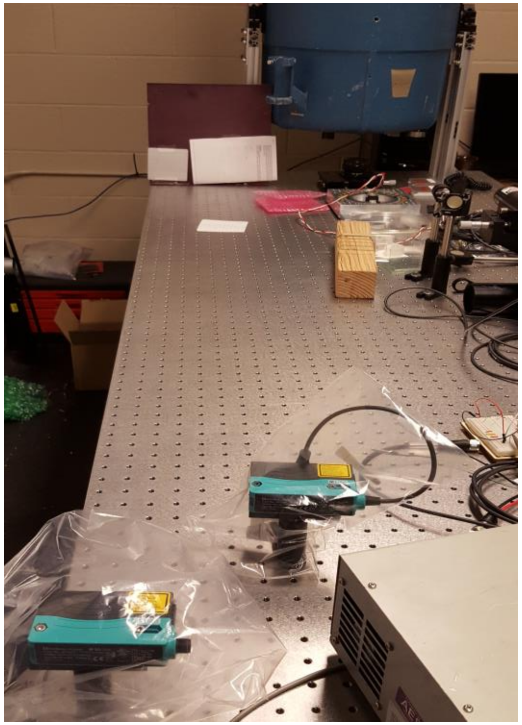
Test Process

- Place mockup centered at nadir
  - Verify mockup is correctly represented by a full scan
- Place mockup with edges aligned with 20° outer scan radius
  - Verify mockup is correctly represented by a full scan
- Producing accurate results at these locations verifies correct operation at extremities
  - Verifies full capabilities

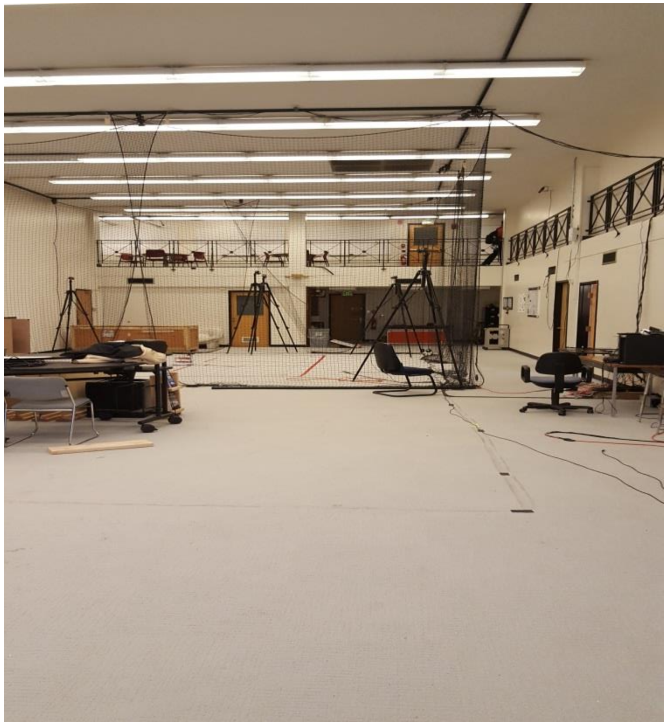


Facilities

- ARSENL
  - Optics bench
  - Component testing



- RECUV Lab
  - Length = 21.7 m
  - Height = 9.5 m
  - Width = 9.2 m
  - Full-scale testing



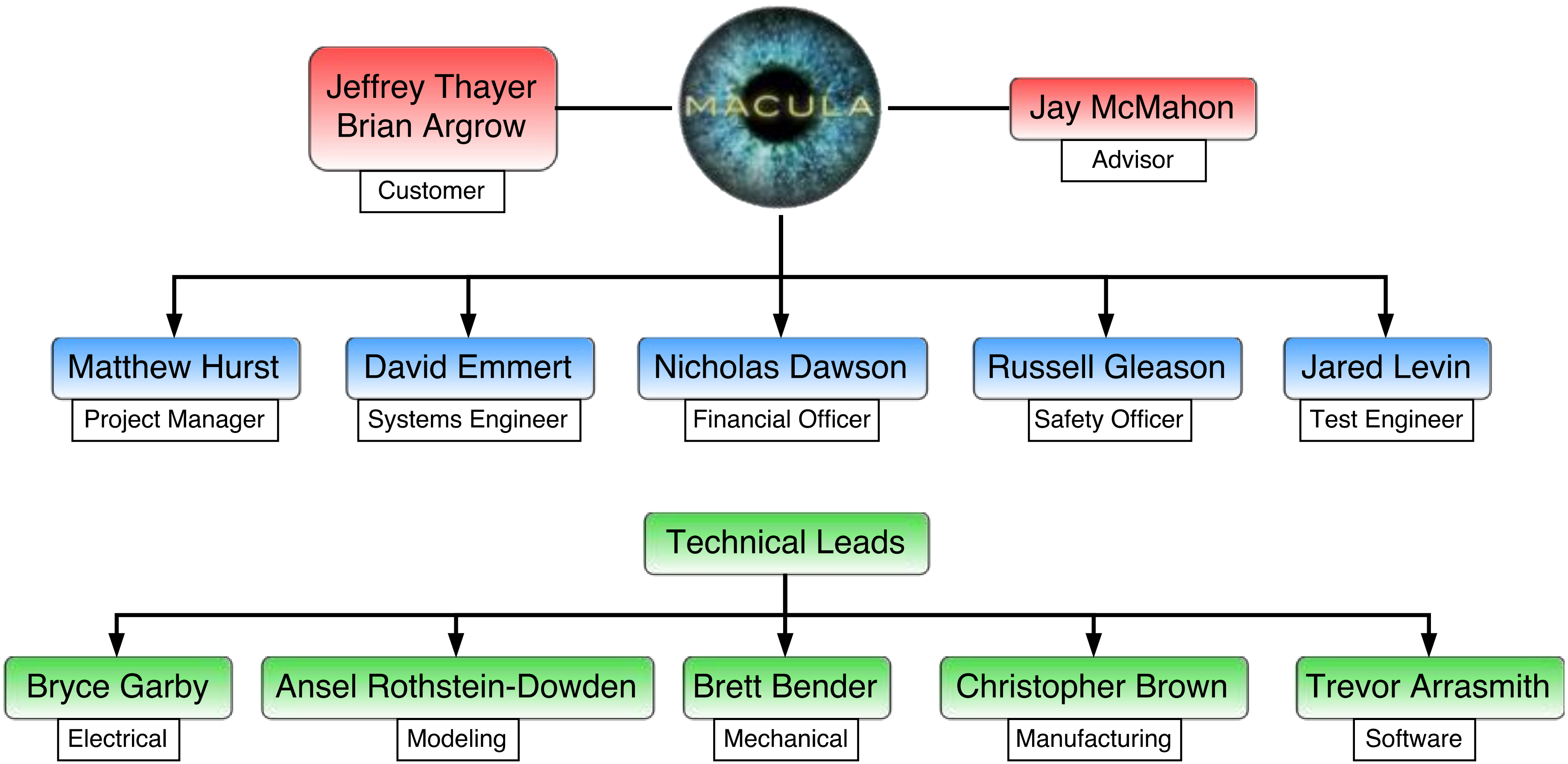
Equipment

- Wood
  - Physical landing zone mockup
- Measuring devices
  - Tape measure
    - Measure large distances
    - Construct landing zone mockup
    - ± 3.5 mm
  - Calipers
    - Construct landing zone mockup
    - ± 0.02 mm
  - Theodolite
    - Accurately determine angles and heights for calibration tests
    - ±2-9 arcseconds ≈ ± 1 mm height measurement
- Optics bench
  - Component-level testing

iStockphoto.com/pryzmat

PROJECT PLANNING

Organizational Chart



Work Breakdown Structure

Project MACULA

- **Structure**
  - Preliminary Design
  - Detailed Design
  - Tolerance Analysis
  - Optomechanical Adjust Design
  - Final Drawings
  - Raw Material/Stock
  - **Assembled Structure**
  - Tested System
- **Embedded System**
  - Component Selection
  - Interface Specification
  - Raw Components
  - Assembled System
  - Tested System
- **Hazard Detection**
  - Develop Code Prototype
  - Test Code Prototype
  - Code on Microprocessor
  - Tested Code
- **Integration and Test**
  - Test Planning
  - Manufacture Test Mockup
  - **Full System Integration**
  - **Full System Testing**
- **Fall Semester Deliverables**
  - Project Definition Doc.
  - Conceptual Design Doc.
  - UROP Application
  - EEF Application
  - Preliminary Design Review
  - Critical Design Review
  - **Fall Final Report**
- **Spring Semester Deliverables**
  - Manufacturing Status Review
  - Test Readiness Review
  - AIAA Paper
  - Spring Final Review
  - Project Final Report
  - Senior Design Symposium

Legend

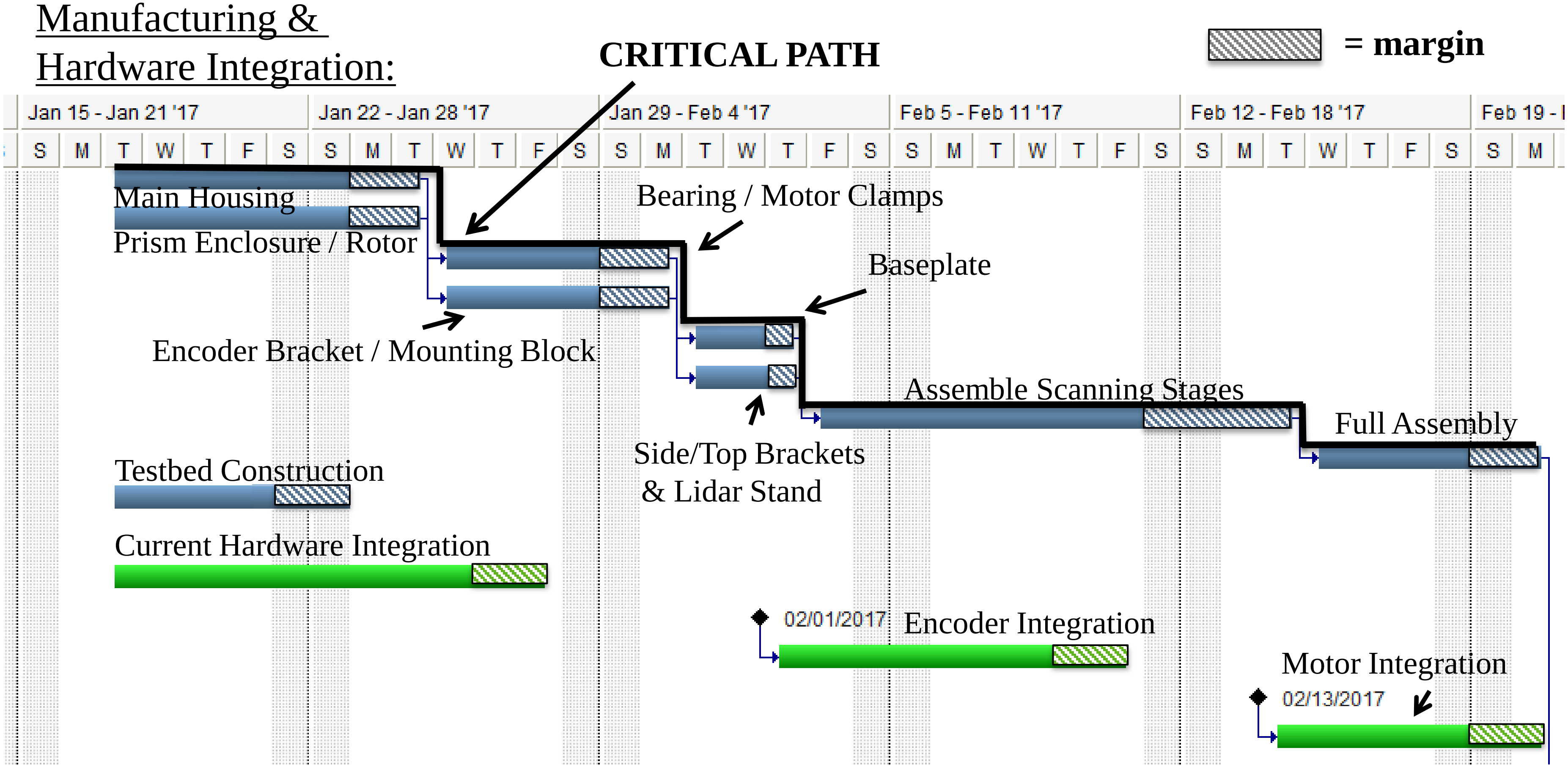
- Complete as of CDR (green)
- Not complete as of CDR (red)

Complete as of CDR: Preliminary Design, Detailed Design, Tolerance Analysis, Optomechanical Adjust Design, Final Drawings, Component Selection, Interface Specification, Develop Code Prototype, Test Code Prototype, Test Planning, Project Definition Doc., Conceptual Design Doc., UROP Application, EEF Application, Preliminary Design Review, Critical Design Review.

Not complete as of CDR: all other items.

Work Plan

Manufacturing &
Hardware Integration:



- Note: Encoder Hub will be manufactured before winter break

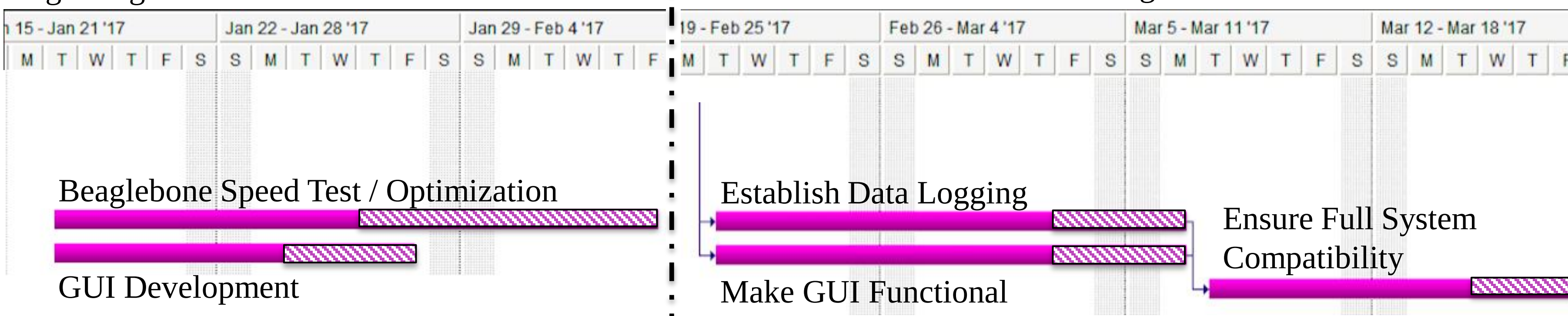
Work Plan

Software:

= margin

Beginning of Semester:

Once encoders and motors are integrated:



Cost Plan

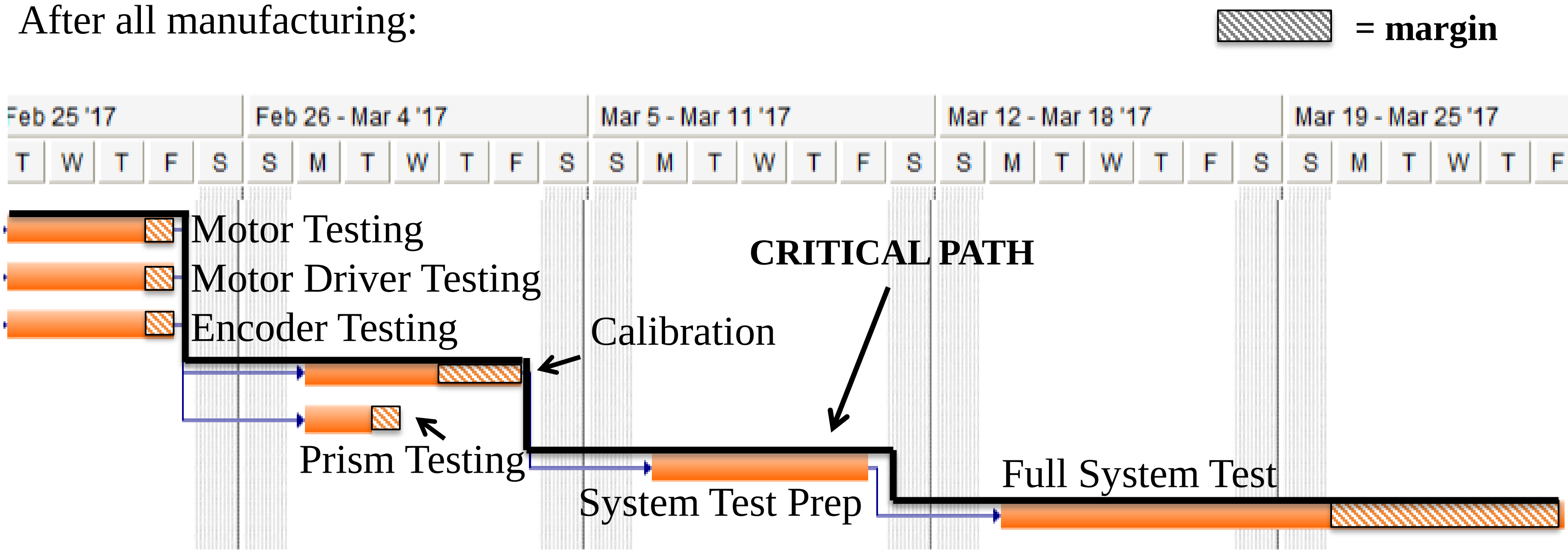
Item	Quantity	Cost per (USD)	Discount (USD)	Total cost (USD)
Lidar:				
Pepperl-Fuchs VDM28-15-L-IO/73c/110/122	1	470.17	470.17	0
Motors:				
ULT-165-A-12-A-x-00x	1	1033		1033
Encoders:				
OPS read head (OD 3.937" ID 2.756")	2	560		1120
Bearings:				
VA030CP0 Thin Section Bearing 3"x3 1/2"x1/4" inch Open	4	81.77		327.08
Microprocessor:				
BeagleBone Black Rev C.1	1	55		55
Reflective Tape				
Oralite (Reflexite) R99 Rail Microprismatic Retroreflective Conspicuity Tape: 4 in. x 15 ft.	9	36.22		325.98
Motor Drivers:				
DPRALTE - 020B080	2	605	363	847
Risley prism:				
P-WRC059 coated with BBAR 400-700 nm	2	108		216

Cost Plan

Item	Quantity	Cost per (USD)	Discounts (USD)	Total cost (USD)
Materials				
Mat: Misc electronics				300
Mat: Fasteners				166
Mat: Stock				0
Mat: Tooling				812
Shipping (assuming $15 per item)				330
Total (Cost)				**6381.83**
Budget			CU Aerospace	5000
			UROP	1000
			Customer	2300
Total (Budget)				**8300**
Percent Margin				**23.11%**

Test Plan

After all manufacturing:



Acknowledgements

Advisor: Jay McMahon

PAB: James Nabity, Kaley Pinover, Brian Argrow, Bobby Hodgkinson, Matt Rhode, Trudy Schwartz, Bob Marshall, Josh Stamps, Jelliffe Jackson

Active Remote Sensing Lab: Jeff Thayer, Rory Barton-Grimley, Bobby Stillwell

Computational and Mechanical Geometry Lab: John Evans, Luke Engvall, Joseph Benzaken

Dale Lawrence

Blue Canyon Technologies: Steve Steg, Matt Carton, Bryce Peters

Pepperl+Fuchs: Michael Turner

QUESTIONS?

Backup Master

Main:

Backup:

References

“AMG Series Optical Mounts & Gimbals.” Aerotech. Aerotech Inc., n.d. Web. 22 Sept. 2016. <https://www.aerotech.com/product-catalog/gimbals-and-optical-mounts/amg.aspx>.

Berg, Mark . Computational Geometry: Algorithms and Applications. Berlin: Springer, 2008. Print.

By FAS — March 23, 2016. “Federation Of American Scientists -.” Federation Of American Scientists. N.p., n.d. Web. 24 Sept. 2016.

Cryan, Scott, and Christian, John A. “A Survey of LIDAR Technology and its Use in Spacecraft Relative Navigation.” AIAA Guidance, Navigation, and Control (GNC) Conference, Boston, MA, 19-22 Aug. 2013. Web.

Dunbar, Brian. “Lidar Atmospheric Sensing Experiment (LASE): Measuring Water Vapor, Aerosols and Clouds.” NASA. NASA, 21 Nov. 2004. Web. 24 Sept. 2016.

Folger, Jean. “Why Curiosity Cost $2.5 Billion.” Investopedia, LLC. 5 Sept. 2012. Web.

Hughes, T. J. R, J. Cottrell A., and Y. Bazilevs. “Isogeometric Analysis: CAD, Finite Elements, NURBS, Exact Geometry and Mesh Refinement.” Computational Methods in Applied Mechanics and Geometry 194.39-41 (2005): 4135-195. Web.

Gonzales, Rafael C. Digital Image Processing. 3rd ed. N.p.: Pearson Education International, n.d. Print.

“LeddarTech Launches LeddarVu, a New Scalable Platform Towards High-Resolution LiDAR.” PR Newswire Association LLC. Quebec City, 7 Sept. 2016. Web.

References

"LiDAR, Laser Scanners and Rangefinders." RobotShop, Inc. 2016. Web. <http://www.robotshop.com/en/lidar.html >

Lynch, Andrew, and Kai Focke. "Beam Manipulation: Prisms vs. Mirrors." Photonik International (n.d.): n. pag. Mar. 2009. Web. 20 Sept. 2016. <http://www.edmundoptics.com/globalassets/resources/articles/beam-manipulation-prisms-vs-mirrors-en.pdf>.

"Puck LiDAR: Our Lightest Yet." Velodyne LiDAR, Inc., 2016. Web. <http://velodynelidar.com/vlp-16-lite.html>

"Round Wedge Prisms." Round Wedge Prisms. THORLABS, n.d. Web. 20 Sept. 2016. <https://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=147 >.

Saniee, Kamron. "A Simple Expression for Multivariate Lagrange Interpolation." SIAM (2007): n. pag. Web.

Schwarze, Craig. "A New Look At Risley Prisms." Photonics Spectra (n.d.): n. pag. Photonics Media, June 2006. Web. 20 Sept. 2016.

Shan, Jie, and Charles Toth K. Topographic Laser Ranging and Scanning: Principles and Processing. Boca Raton: CRC/Taylor & Francis Group, 2009. N. pag. Print.

Shewchuk, J. "What is a good linear finite element? interpolation, conditioning, anisotropy, and quality measures (preprint)." University of California at Berkeley 73 (2002).

References

"Technology Overview." Advanced Scientific Concepts, Inc. 2015. Web. <http://www.advancedscientificconcepts.com/technology/technology.html >

Wilsenack, Frank. "Defense & Security." Detecting and Tracking Thin Aerosol Clouds. SPIE, 12 Oct. 2012. Web. 24 Sept. 2016.

Y. Bazilevs et al., Isogeometric analysis using T-splines, Comput. Methods Appl. Mech. Engrg. (2009), doi:10.1016/ j.cma.2009.02.036

Riemersma, Thiadmer. "Candela, Lumen, Lux: the equations." CompuPhase, 2016. Web.

"Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting Utilizing the Coplanar Geometry." ASTM International, Designation E 810-03, 2016. PDF.

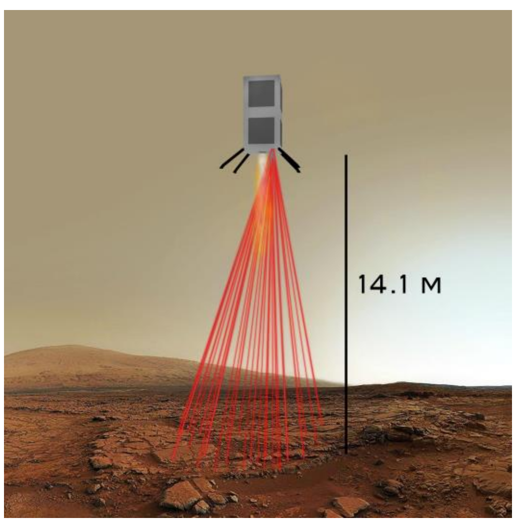
"Pepperl+Fuchs VDM 28 Photoelectric Sensor Datasheet." Pepperl+Fuchs, 2016. PDF.

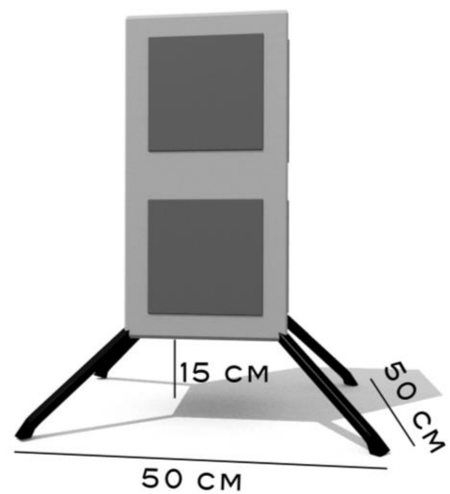
"Reflexite Daybright V92 Conspicuity Sheeting." Reflexite America, 2006. PDF.

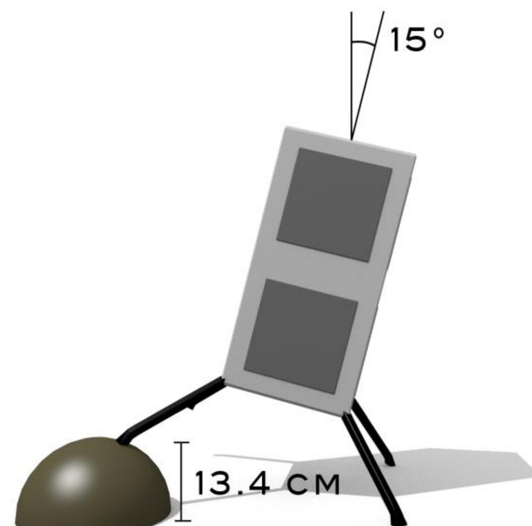
BACKUP: GENERAL CONCEPT

CubeSat Lander Concept

- Landing hazard definition based on hypothetical CubeSat lander dimensions
- Hazards (obstacles and gradients) identified where the lander could land more than 15° off of vertical
- Scanning resolution of 10 cm selected to detect ~98% of potential hazards

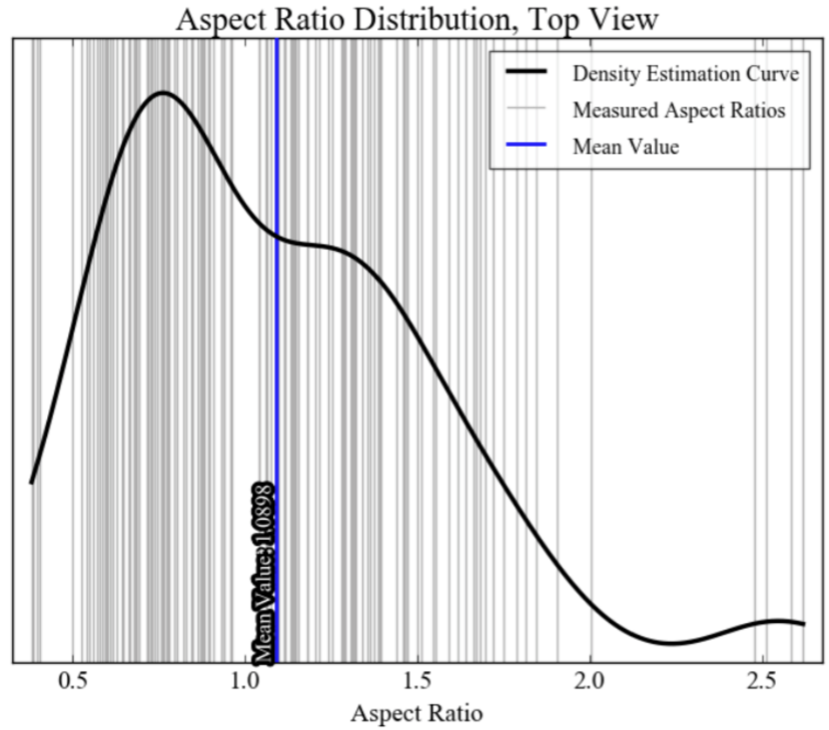






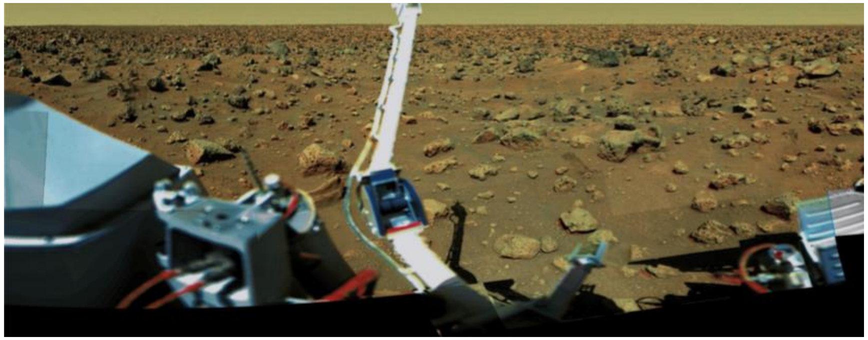
Top View Martian Rock Analysis

Top view of Martian surface

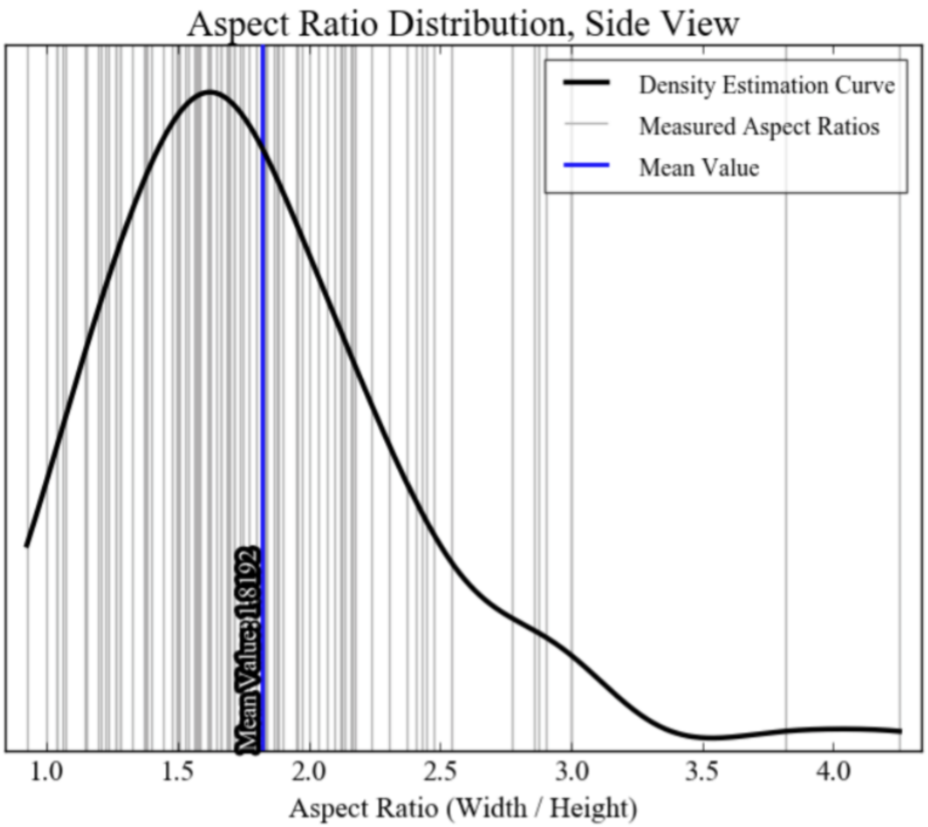


Aspect ratio distribution

Side View Martian Rock Analysis



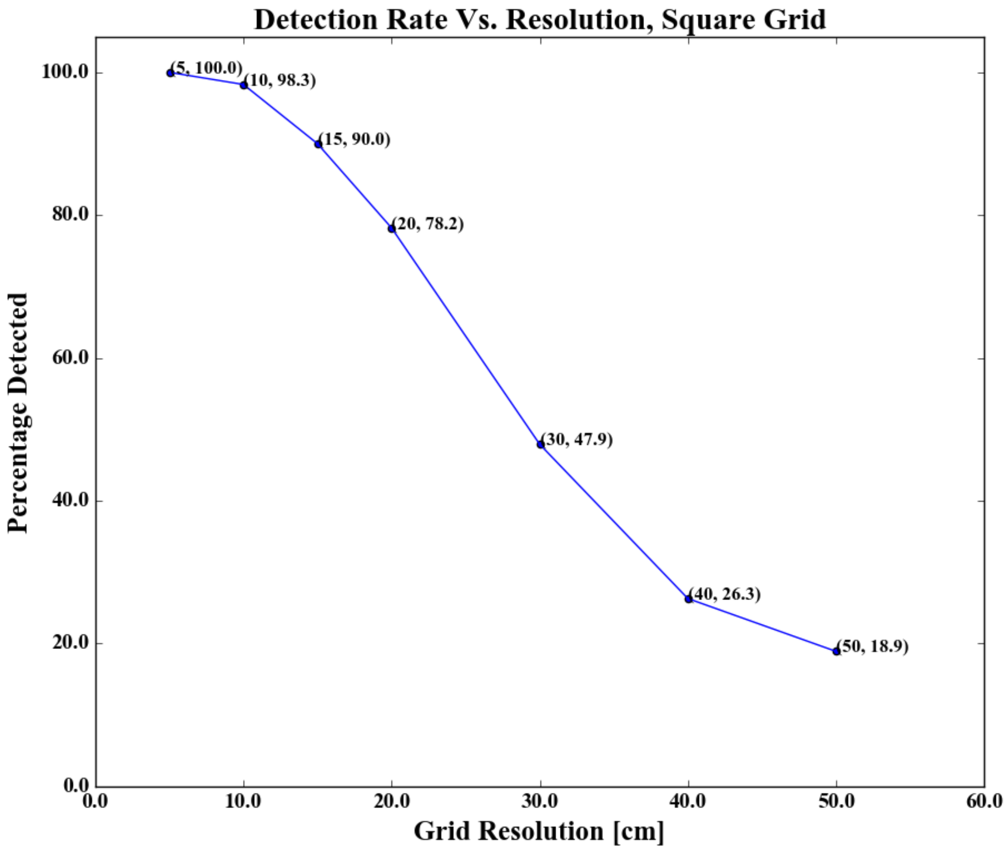
Side view of Martian surface



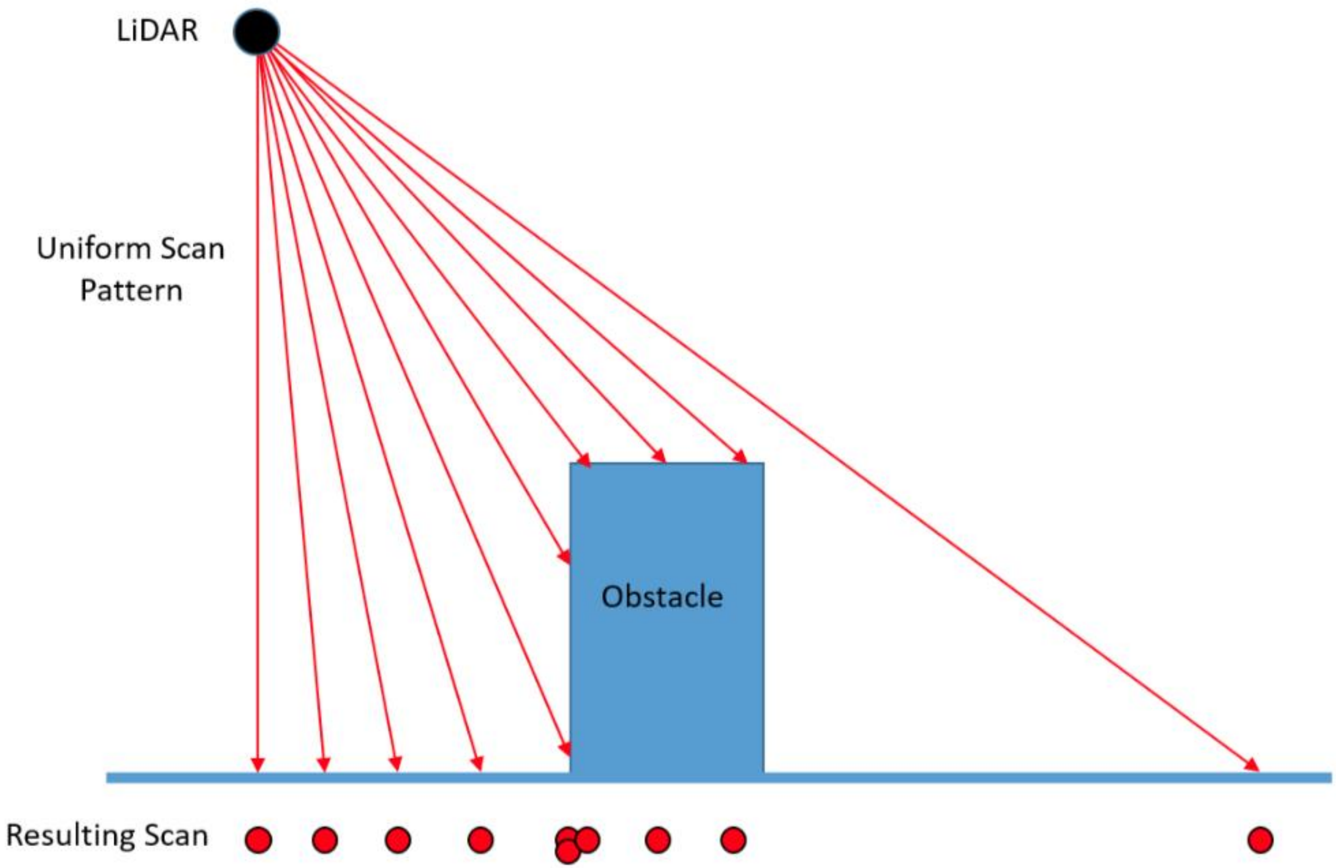
Aspect ratio distribution

Resolution Requirement

- Statistical analysis of rock size/aspect ratios on Mars
- Created a software map of a characteristic landing surface
- Monte Carlo simulation with different scan resolutions
- Determine probability of aliasing over a hazard (failure) vs. scan resolution

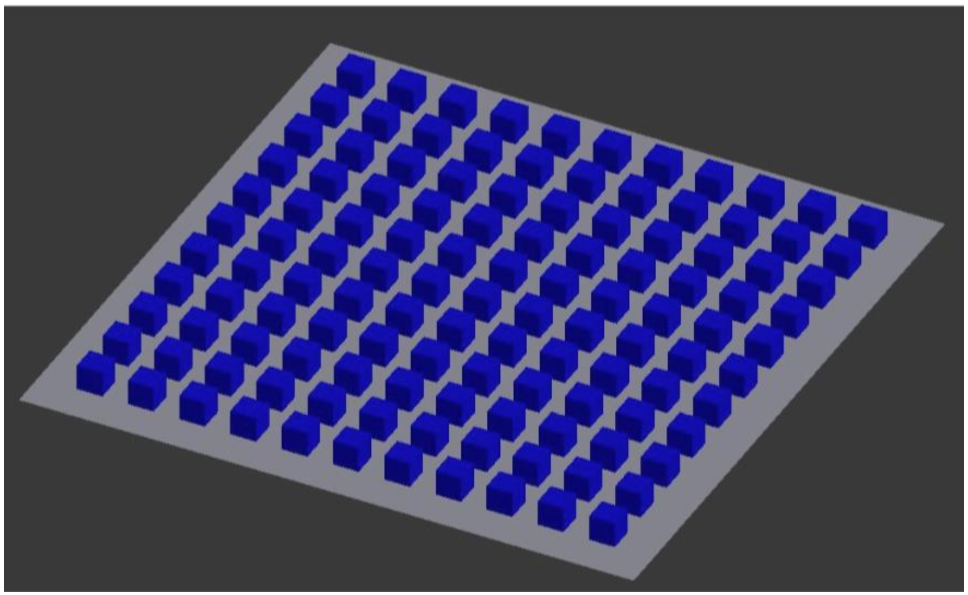


Shadowing

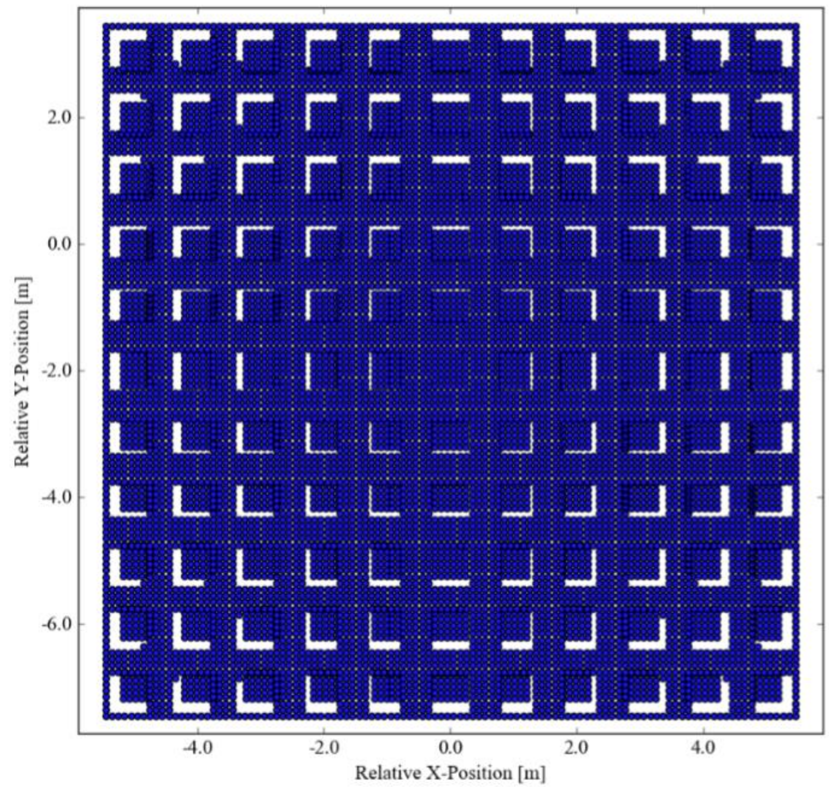


Visualization of shadowing effects

Maximum Scan Angle



Blender visualization of a test scene



Resulting points with lidar scan

BACKUP: DESIGN REQUIREMENTS

FR 1

1. The system shall analyze a potential landing zone for a 12U cubesat.
   1.1. The system shall scan up to a half-angle of 20° off of nadir.
   1.2. The system shall scan from a nadir range of 14.1 m.
   1.3. The system shall scan with a resolution of better than 0.1 m.
      1.3.1. The error in this resolution shall be less than 0.05 m in the plane of the scan area.
   1.4. The system shall complete the scan and analysis in less than 60 seconds.
      1.4.1. The system shall complete the scan in less than 50 seconds.
      1.4.2. The system shall complete the analysis in less than 10 seconds.

FR 2

2. The on-board processor (OBP) shall receive commands and data from a user-operated PC (UPC).
   2.1. The OBP shall execute a main driver routine.
      2.1.1. While executing the main driver, the OBP shall receive a “ready” command from the UPC.
      2.1.2. After a “ready” command is received, the OBP shall receive a “start command from the UPC.
      2.1.3. During operation (after a “start” command) the system shall receive a “stop” command from the UPC.
         2.1.3.1. Upon receiving a “stop” command, the system shall stop operation (cut power to the lidar and the motors) within 1 second.

FR 2

2. The on-board processor (OBP) shall receive commands and data from a user-operated PC (UPC).
   - 2.2. Outside of the main driver, the OBP shall receive and store data from the UPC.
     - 2.2.1. The OBP shall receive and store in memory a list of Risley Prism orientations for the desired scan.
     - 2.2.2. The OBP shall receive and store in memory a list of simulated IMU values for the spacecraft.
       - 2.2.2.1. These IMU data shall be a Direction Cosine Matrix (DCM) for the system at each scan time, relative to the scan surface.
     - 2.2.3. The OBP shall retain memory while powered and unpowered.
     - 2.2.4. The OBP shall be programmable so that stored data and routines can be modified through the interface with the UPC.

FR 3

3. The OBP shall command the sensor package (SP).
   - 3.1. The OBP shall control power (on or off) to the lidar sensor.
   - 3.2. The OBP shall control power (on or off) to the motors.
   - 3.3. The OBP shall send commands to the motor drivers.
     - 3.3.1. The OBP shall read the data file of Risley prism orientations to send to the motors.
     - 3.3.2. The desired prism orientations must be updated at least once every 10 ms.

FR 4

4. The SP shall use a fixed-beam lidar sensor to obtain range measurements.
   - 4.1. The lidar shall operate within a range of 12 m - 15 m.
   - 4.2. The lidar shall have a range error with a standard deviation of less than 2.5 cm at all ranges between 12 m and 15 m.

FR 5

5. The SP shall have control over the lidar beam direction using two Risley prisms.
   - 5.1. The Risley prisms shall be capable of actuating the beam across the entire scan area.
     - 5.1.1. The Risley prisms together shall be capable of deflecting the lidar beam by at least 20° from nadir.
   - 5.2. The Risley prisms shall be individually controlled in order to direct the lidar beam.
     - 5.2.1. The Risley prism actuation system shall be capable of producing sufficient torque to achieve 15 rad/s^2.
     - 5.2.2. The Risley prism actuation system shall be capable of producing angular rates between 0 rad/s and 10 rad/s.
   - 5.3. After system calibration, the lidar shall have a cross-range error with a standard deviation of less than 2.5 cm for all locations in the scan area.
     - 5.3.1. The sum of two standard deviations plus the radius of the beam spot shall not exceed 5 cm at any point in the scan area.
     - 5.3.2. The Risley prism orientations shall be known to within 0.1° about the axis of rotation.

FR 5

5. The SP shall have control over the lidar beam direction using two Risley prisms.

5.4. The SP shall not inhibit the lidar sensor from receiving a return signal.

5.4.1. The Risley prism receiver field of view shall be less than 50% obscured.

5.4.2. The transmissivity of the Risley prisms shall allow for a beam return of at least 90% strength, assuming a perfect specular retroreflection from the target.

5.4.2.1. The Risley prisms shall be covered with an anti-reflective coating appropriate for the lidar wavelength.

5.4.3. The Risley prism actuation system shall not impede the optical path of the lidar beam for any orientation within the scan area.

FR 6

6. The OBP shall receive data from the SP.
    - 6.1. The OBP shall read and save the lidar range measurement to memory every 10ms.
        - 6.1.1. The output of the lidar sensor shall be converted into a voltage.
        - 6.1.2. The voltage shall be readable by the OBP Analog to Digital Converted (ADC).
            - 6.1.2.1. The ADC shall have a resolution of at least 12 bits.
    - 6.2. The OBP shall read the prism orientation measurements.
        - 6.2.1. The OBP shall read the quadrature output of the each encoder continuously to translate into a count.
            - 6.2.1.1. Each count shall be translated into an absolute angular position of each prism.
        - 6.2.2. Each prism orientation shall be saved to memory every 10ms.
    - 6.3. The lidar range measurement and prism orientations shall be correlated such that prism orientations from t=0 match with lidar ranges from t=5ms.

FR 7

7. The OBP shall project the SP data into a three-dimensional (3D) point-cloud.
   7.1. The OBP shall translate the prism orientations into a location (origin) for the outgoing lidar beam.
   7.2. The OBP shall translate the prism orientations into a direction vector for the outgoing lidar beam.
   7.3. The OBP shall project the range measurement along the computed direction vector, then add this to the computed origin to find a point in an intermediate cartesian frame relative to the lidar emitter.
   7.4. The OBP shall rotate the point in the intermediate frame into an inertial frame using the simulated IMU data.
   7.5. These calculations shall occur as the scan is being completed.

FR 8

8. The OBP shall analyze the 3D point-cloud to identify hazardous locations.
   8.1. The OBP shall begin analysis once the scan points have reached a distance of 0.45 meters from nadir.
   8.2. The OBP shall process a scan point by finding all points within the error-compensated lander footprint range, then computing the maximum height difference between of all these points. A safe point is one where this difference does not exceed the error-compensated hazard height.
   8.3. The points shall be analyzed in the order in which they arrive.
   8.4. A point shall be analyzed if and only if it is the next point in the queue and the distances from nadir of the most recently found points has exceeded the sum of the distance of the queued point from nadir and its error-compensated lander footprint range.

FR 9

9. The OBP shall select an acceptable landing site.
    9.1. The OBP shall identify the first computed safe point as the acceptable landing site.

FR 10

10. The OBP shall generate output readable by the UPC.
    10.1. The OBP shall generate health and status information readable by the PC in real time.
        10.1.1. The OBP shall provide a status message to the UPC once per second while the system is driver is running.
            10.1.1.1. The status message shall be "off" if the system is running the driver but is not ready or running.
            10.1.1.2. The status message shall be "warming up" if the system has received the "ready" command but has not yet completed the ready sequence.
            10.1.1.3. The status message shall be "ready" if the system has completed the ready sequence after receiving the "ready" command.
            10.1.1.4. The status message shall be "running" if the system is executing the scan. This message shall be time-stamped relative to the receipt of the "start" command.
            10.1.1.5. The status message shall be "analyzing" if the system has completed the scan but not the analysis. These messages shall be time-stamped with relative to the receipt of the "start" command.
            10.1.1.6. The status message shall be "complete" if the system has completed the scan and analysis. This message shall be time-stamped relative to the receipt of the "start" command.
            10.1.1.7. After a "complete" message is displayed, the system status shall be reset to "off."
            10.1.1.8. The status message shall be "stopped" if the operation was terminated with the "stop" command. This status shall remain in effect until the driver is restarted.

FR 10

10. The OBP shall generate output readable by the UPC.
    - 10.1. The OBP shall generate health and status information readable by the PC in real time.
        - 10.1.2. The health and status information shall appear on the terminal of the UPC once per second.
    - 10.2. The OBP shall save raw sensor outputs to memory.
        - 10.2.1. The OBP shall save lidar sensor measurements to memory.
        - 10.2.2. The OBP shall save prism orientation measurements to memory.
    - 10.3. The OBP shall save translated beam attitudes to memory.
    - 10.4. The OBP shall save x, y, and z coordinates for each point to memory.
    - 10.5. The OBP shall save a SAFE/UNSAFE designation to memory for each point.
    - 10.6. The OBP shall save the coordinates of the selected landing site to memory.
    - 10.7. The saved data for each point shall be correlated.
    - 10.8. The saved data shall be readable on the UPC outside of the driver routine.

Lidar Sensor Sampling

Pepperl+Fuchs VDM28:

- COTS sensor that meets requirements and budget constraints

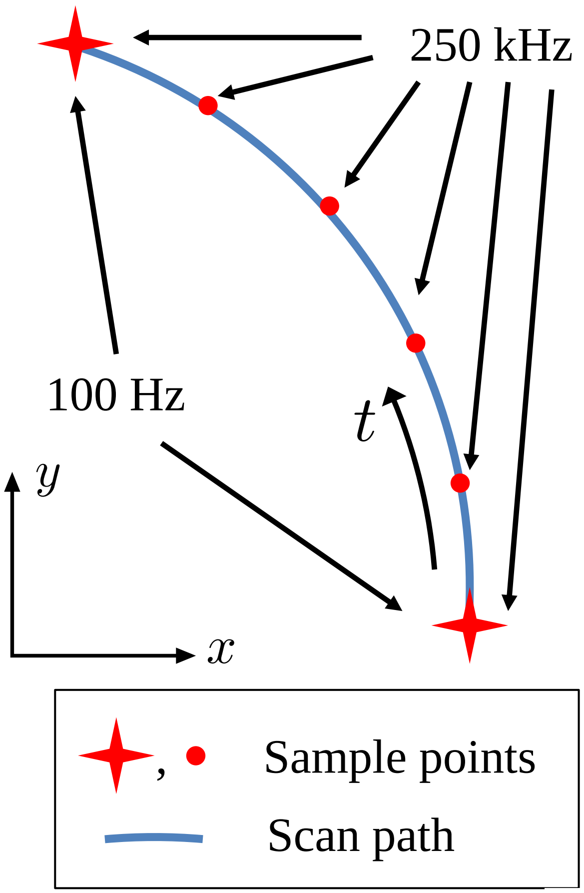
Sensor shortcomings:

- 100 Hz sampling frequency
- Time-averages over 10 ms (takes 2500 samples in that interval)

Possible solution:

- Custom-built sensor with higher sampling frequency and no time-averaging
  - Cost estimate: ~$10,000

point distribution not to scale



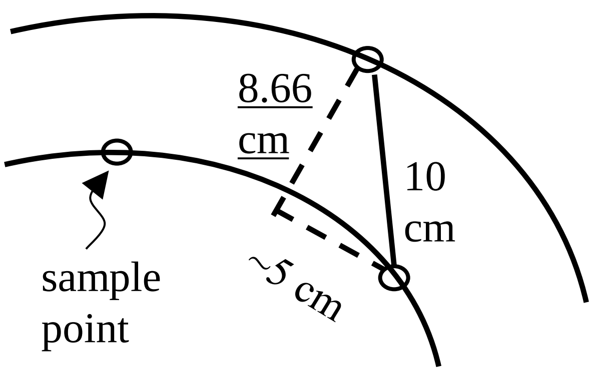
Lidar Sensor Sampling

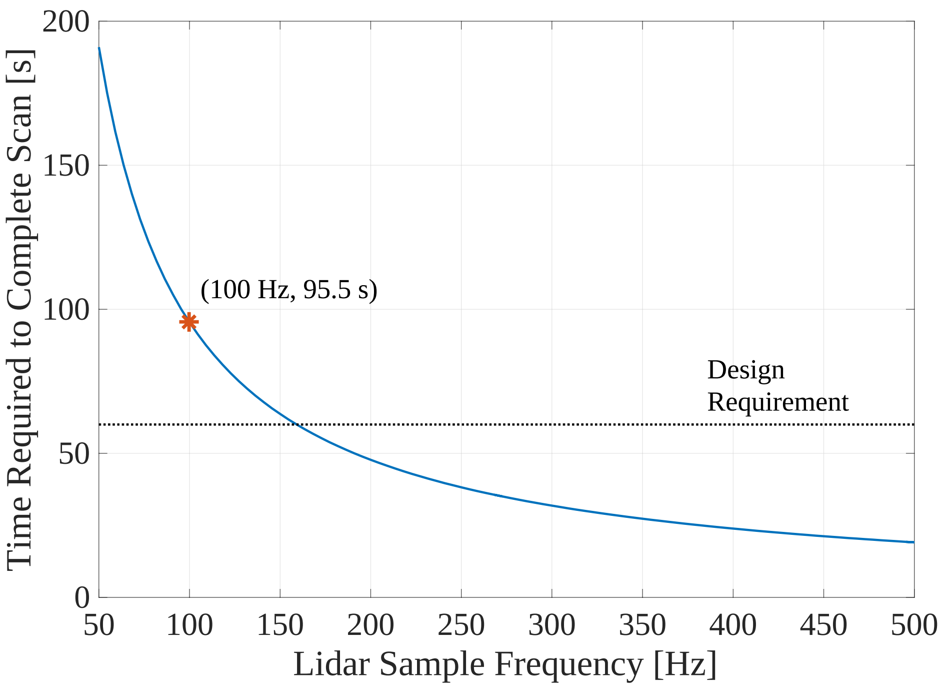
<u>Resolution</u>

- Spiral Spacing: 8.66 cm
- Arc-point Spacing: 10 cm

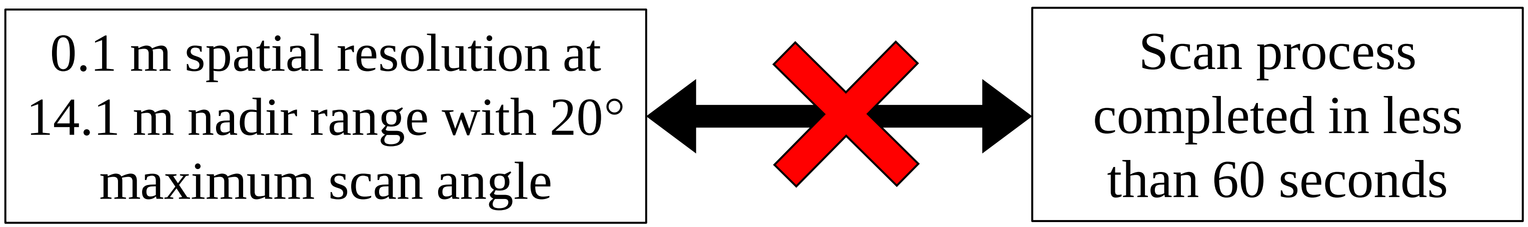
<u>Minimum frequency</u>

- Total points: 9,550
- f_{min} = 159 Hz





Scan Time vs. Scan Resolution



Problem: These two closely coupled objectives cannot be completed concurrently due to financial limitations on the lidar sensor

Lidar Wavelength

Feasibility for MACULA

- Test surface can be constructed with white diffuse paint or white retroreflective tape

Why this sensor was selected

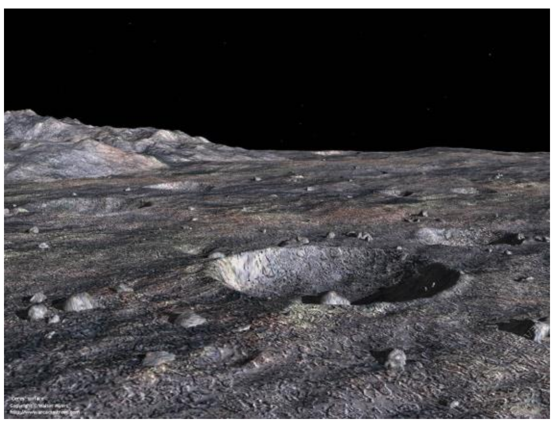
- Meets budget and accuracy constraints
- Test surface can be constructed to fit sensor

Benefits of Using 660 nm

- Visible spectrum (verification)

Lidar Wavelength

- Per **FR1**, MACULA is proof-of-concept system for CubeSat lander
  - Wavelength can be selected for custom-built sensors
  - Implemented systems will choose wavelength based upon landing surface



http://pics-about-space.com/asteroid-surface?p=1

http://pics-about-space.com/planet-mars-surface?p=1

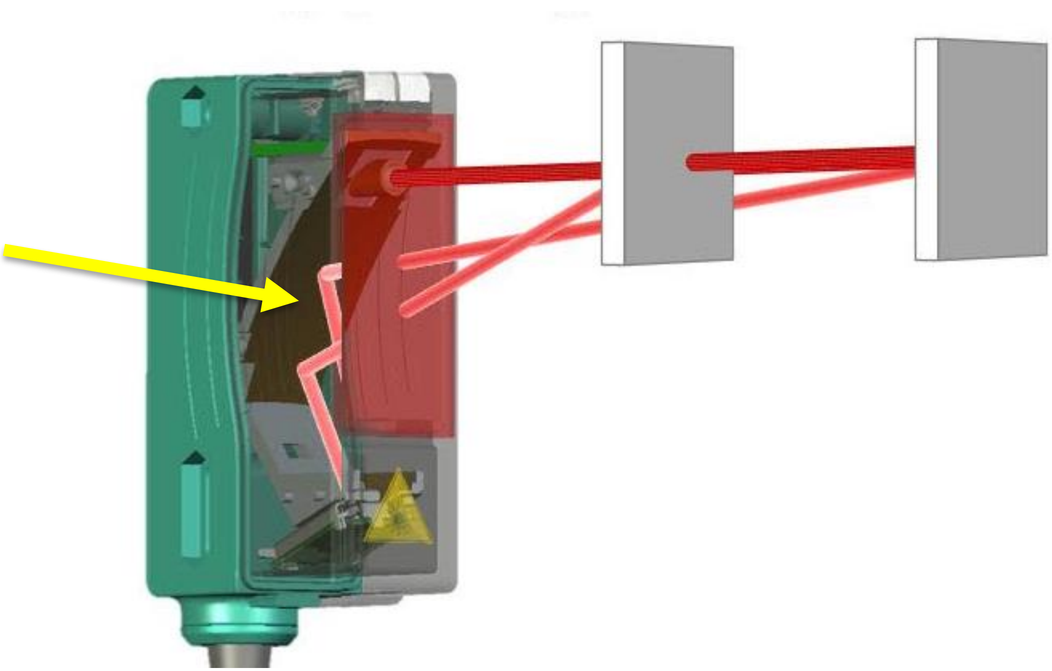
Laser Wavelength vs. Cost

- Red lasers are the most common and cheapest to manufacture
- Laser colors other than red require specialized crystals with rare-earth elements such as Neodymium
  - These extra components can drive up the cost of other color lasers (yellow, blue, green) to dozens of times the cost of a red laser
- These colors can have better reflection on certain surfaces, but do not provide a general advantage over red lasers

Detector Functionality

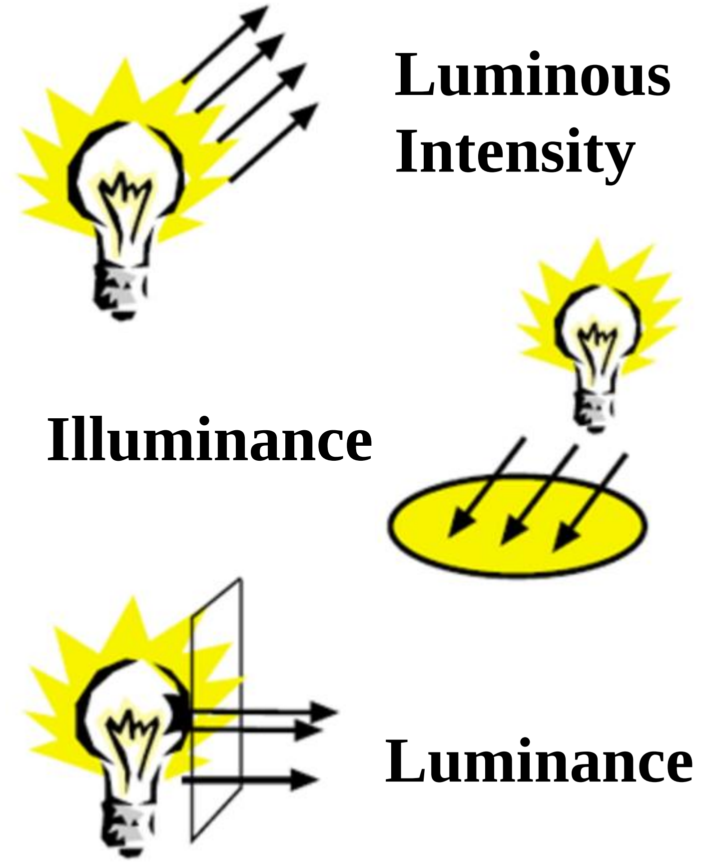
- Parabolic mirror to collect diffuse returns
- Specular returns do not disperse

Parabolic
Mirror



Retroreflection

- Luminous Intensity [candela] – Quantity of luminous flux in given direction
- Illuminance [lux] – Measure of concentration of luminous flux falling on surface
- Luminance [candela/m^2] – Measure of flux emitted from or reflected by a uniform surface

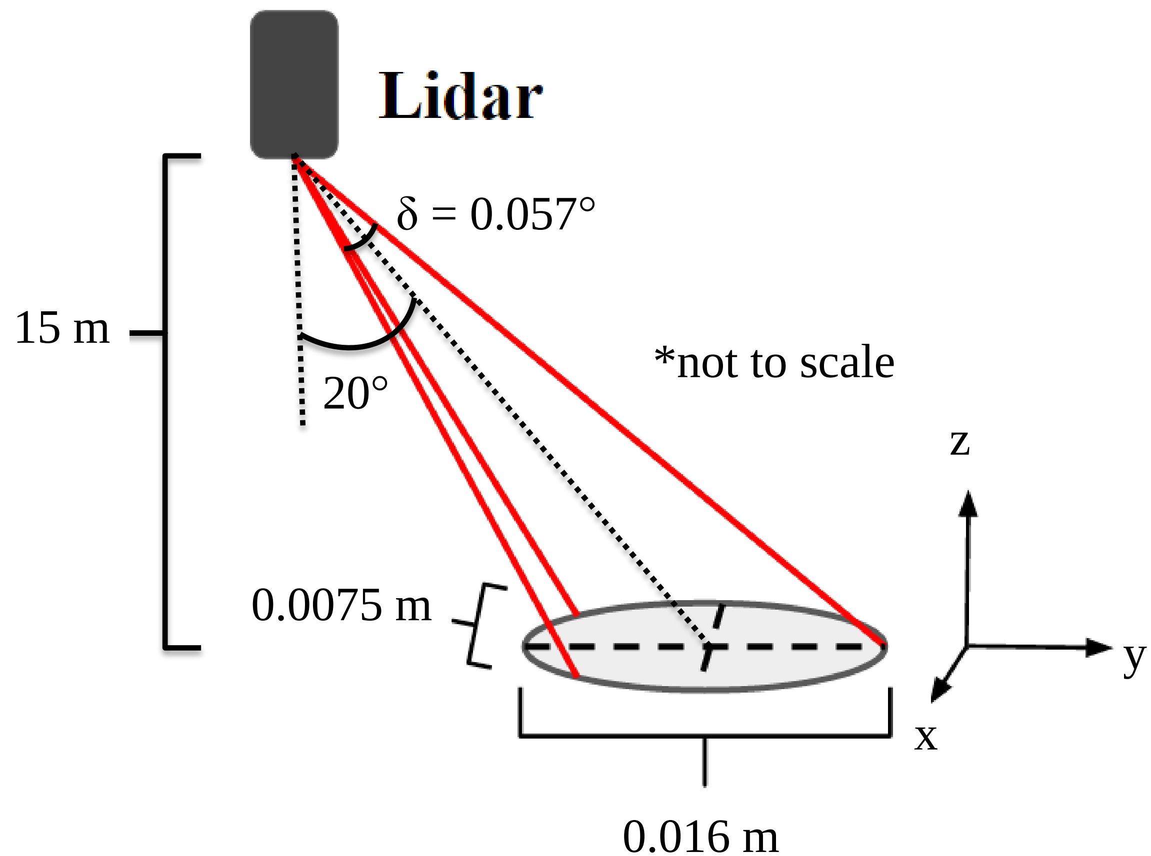


http://www.konicaminolta.com/instruments/knowledge/light/concepts/04.html

Retroreflection

Laser Emitter

- Pulse: < 4 nJ
- Pulse length: 5 ns
- Beam divergence:
  - δ = 0.057°
- Luminous Intensity:
  - 4.24e7 candela
- Illuminance on surface (15 m, 20° from nadir)
  - 1.89e5 lux



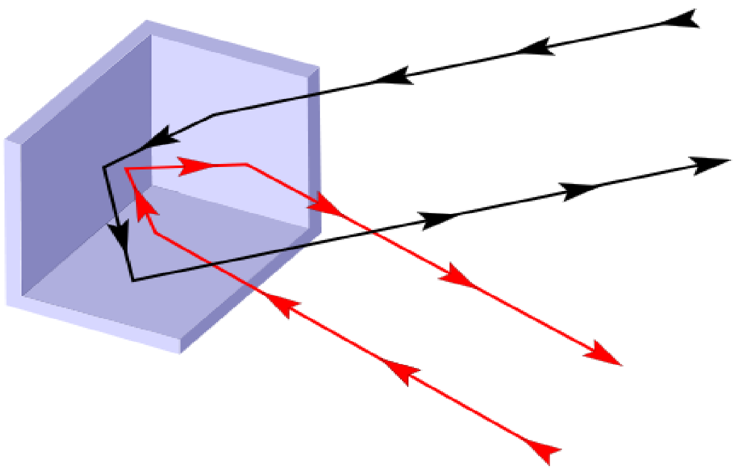
Retroreflection

Reflexite Daybright V92

Observation Angles	Entrance Angles	White
0.2 °	-4 °	460
	30°	250
0.5 °	-4 °	100
	30 °	65

- Luminance of return:
  - 1.23e7 candela/m^2
- Luminance of Pepperl+Fuchs datasheet tests (90% Kodak White):
  - 1.70e5 candela/m^2

Prismatic Retroreflector



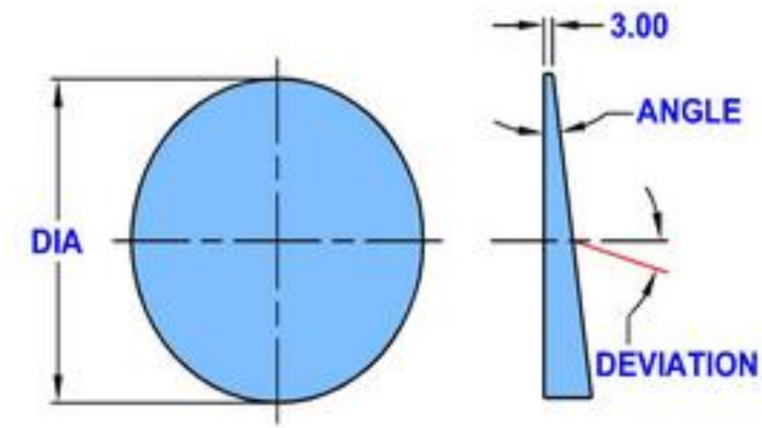
https://en.wikipedia.org/wiki/Retroreflector

Risley Prism Specs

- Suitable for wide range of wavelengths
  - 450 nm - 2000 nm
- Coatings available for 660 nm
  - Reflectance of about 1%, resulting in above 90 % transmissivity
- Cost:
  - $100 each uncoated
  - Additional $5 for coated

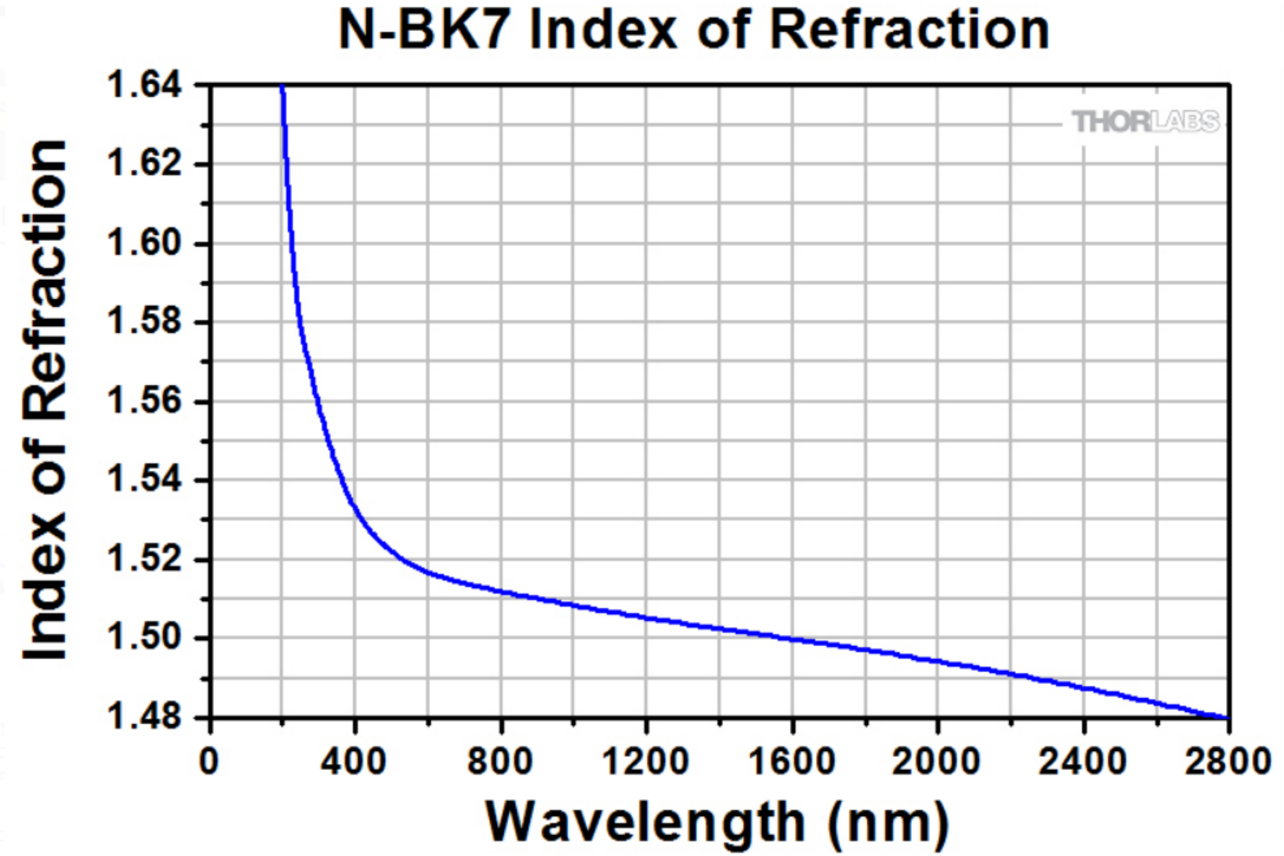
Prism Specifications

- Ross Optical P-WRC059
  - Diameter: 5.08 cm
  - 10° Maximum Beam Deviation (per prism)
  - Wedge Angle: 18° 8′
  - Angle Error: ± 30 arc seconds
  - Material: N-BK7 Grade A fine annealed
    - Transmission: 91% at 660 nm
    - Density: 2.51 g/cm³
    - Thermal Expansion: $7.1 \times 10^{-6}\ \mathrm{K}^{-1}$
  - Thin Edge Thickness: 3mm
  - Dimensional Tolerance ± 0.1 mm

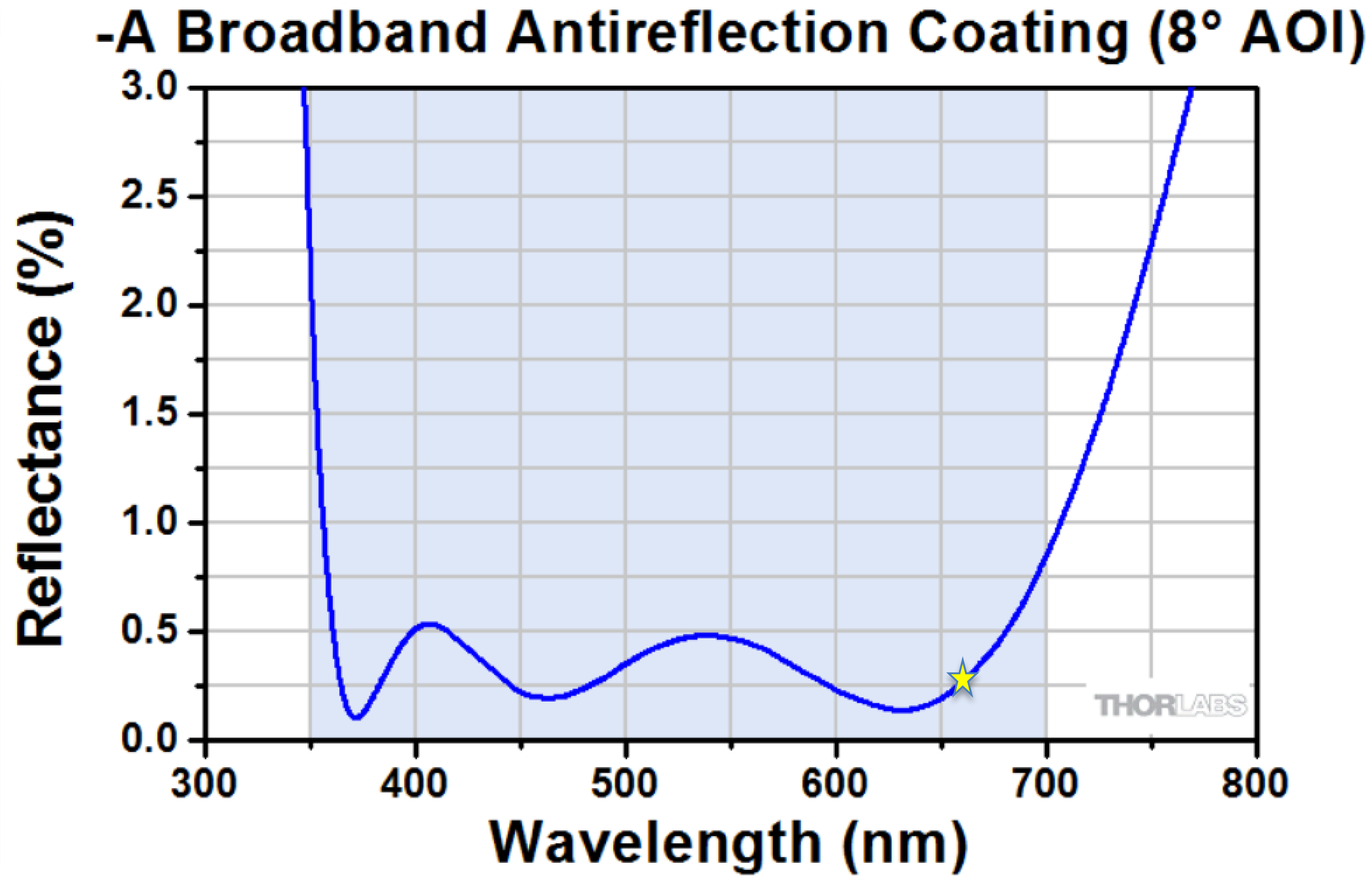


Index of Refraction

- N-BK7 has variable index of refraction

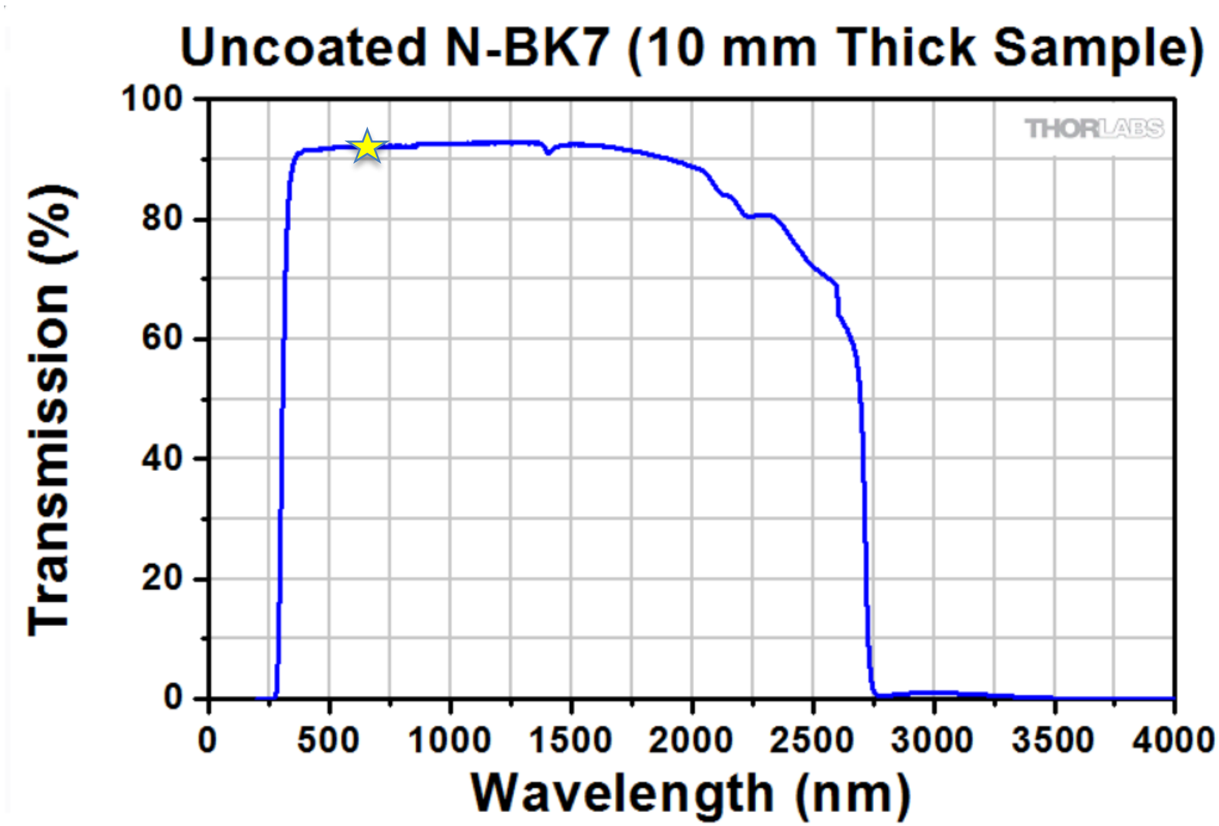


Coating Reflectance



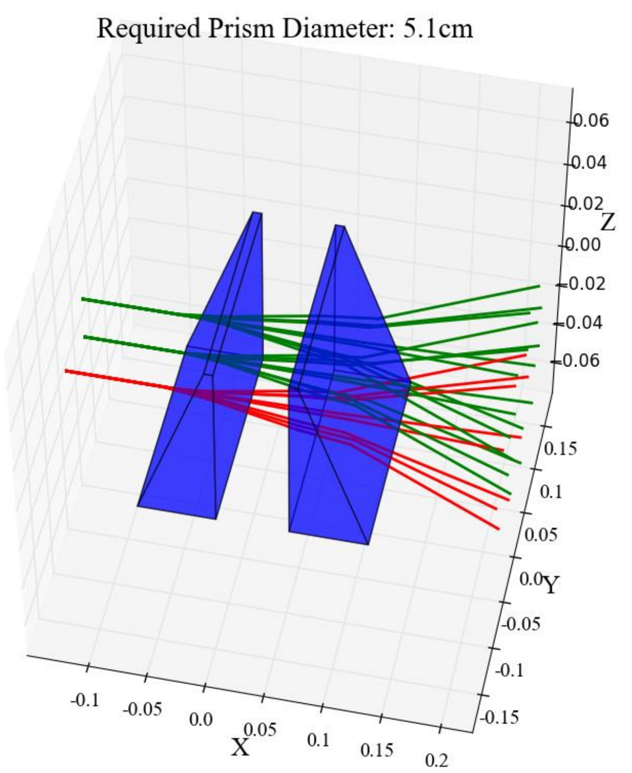
Prism Attenuation

- Material: N-BK7 Grade A fine annealed



Prism Diameter

- Beam lines calculated for eight rotations of the prisms (rotated together to produce maximum deflection angle)
- Transmitter and two points on the edge of the receiver are projected straight and their refractions are calculated for each of the prism rotations
  - This is only part of the receiver field of view. The lidar is placed to maximize what the receiver can see, without clipping the transmitter
- Prism diameter based on the farthest point from the center axis for any beam on any prism face
- Resulting distance is divided by 0.9 to produce the prism diameter (for best refraction results from the prism)
- Modeled as blocks for ease of plotting only. Reported size is the diameter

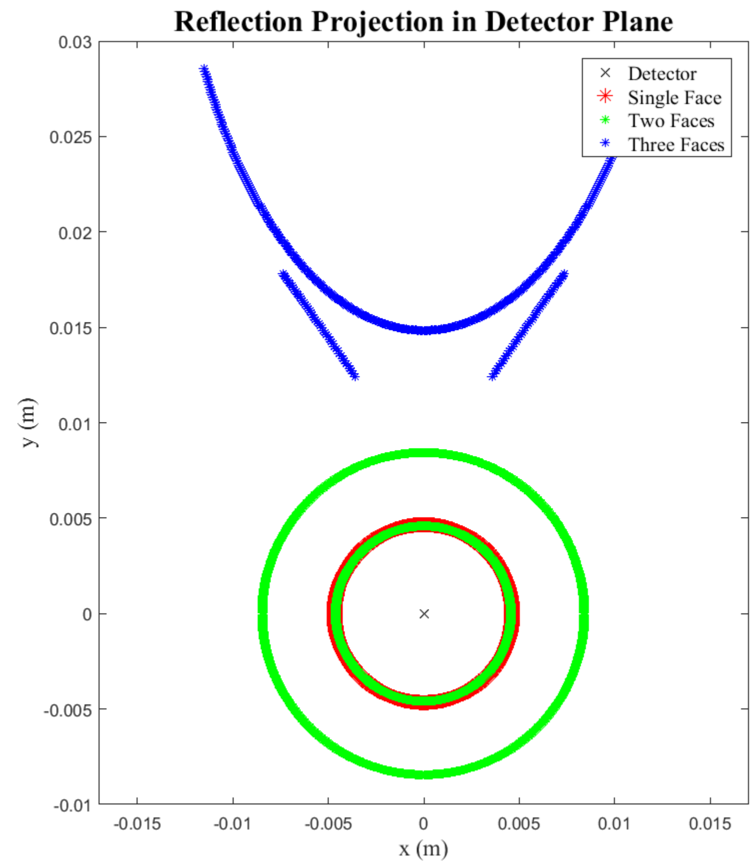


Reflection Analysis

- Possible Risk: Reflections off prisms trigger lidar false returns.

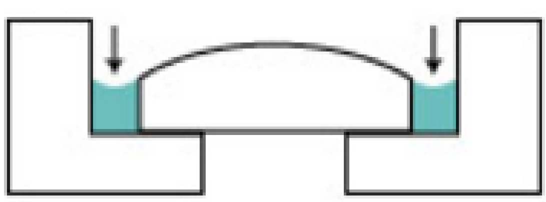
- Reflections were analyzed to determine if they would hit detector.

- This risk can be mitigated by moving lidar away from prisms.



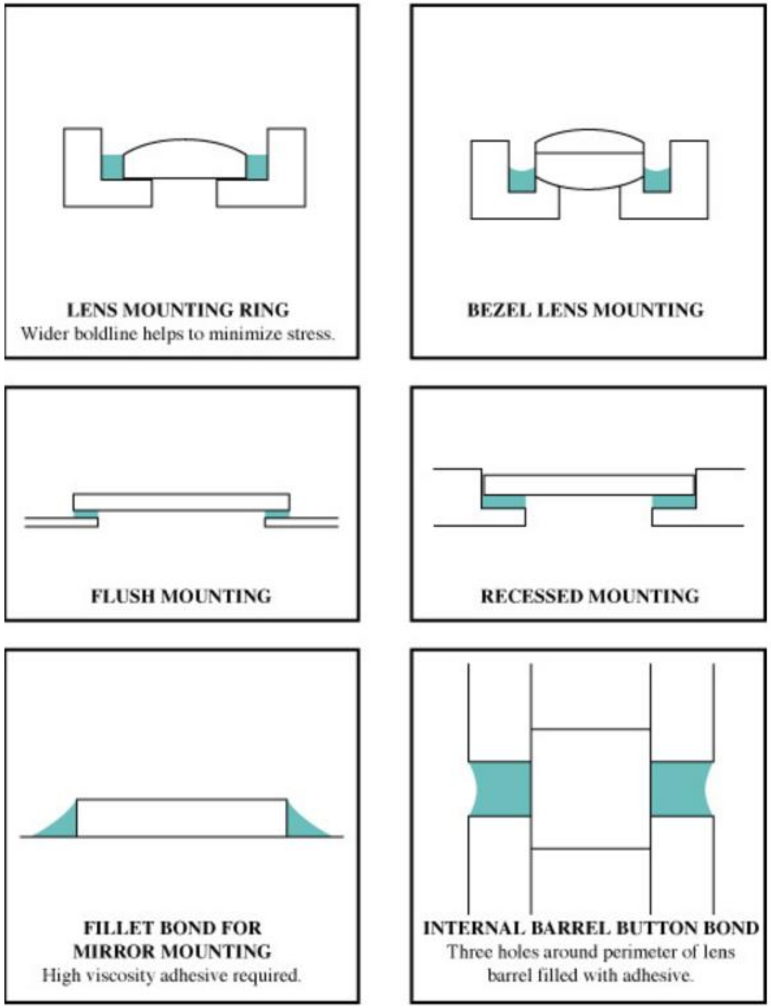
UV Cured Epoxy

- Upon curing, surface of epoxy exposed to UV light shrinks forming a meniscus
- Various techniques can be utilized to minimize stress upon shrinkage.
- Internal Barrel Button Bond method selected. Allows for slip fit and minimal shrinkage stress.



Epoxy Shrinkage shown on the right. Epoxy mounting techniques shown on the left.

https://www.norlandprod.com/techrpts/techniques.html



Epoxy Selection

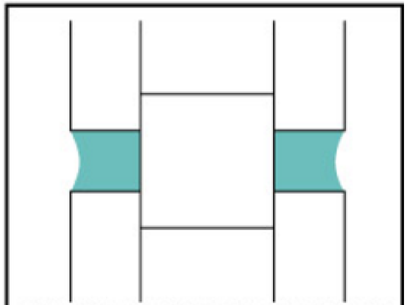
Selected UV Cured Epoxy: Thorlabs NOA81

- Shrinkage: 1.5 %
- Tensile Strength: 4000 psi
- Glass to Metal bond strength: Excellent
- Cost: $33.5
- Amount per bottle: 1 oz
- Recommended Curing Intensity:

  >2 mW/cm^2 @ 365 nm

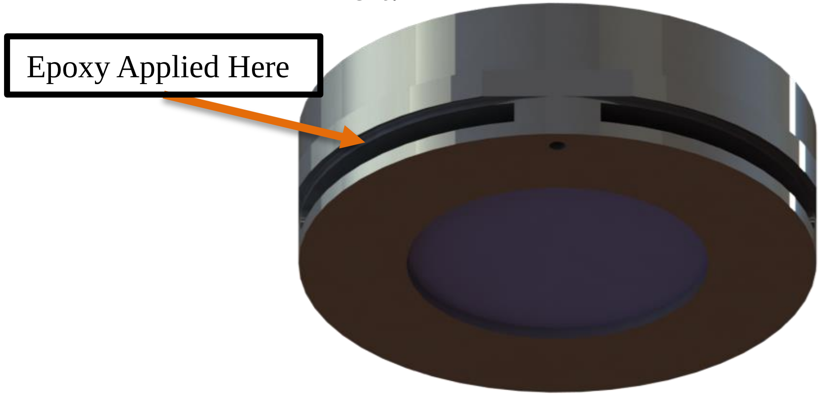
Mounting Stress Analysis

- Allowable Shear Stress: 1000 psi
- Estimated Area Exposed to Epoxy: 0.47 in^2
- Allowable Torque: 470 lb-in or 53.10 Nm
- Maximum Torque Supplied by Motors: 1 Nm
- Very low chance of failure

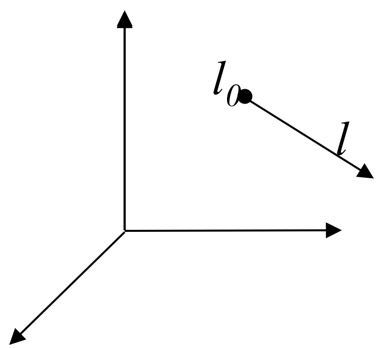


INTERNAL BARREL BUTTON BOND
Three holes around perimeter of lens barrel filled with adhesive.

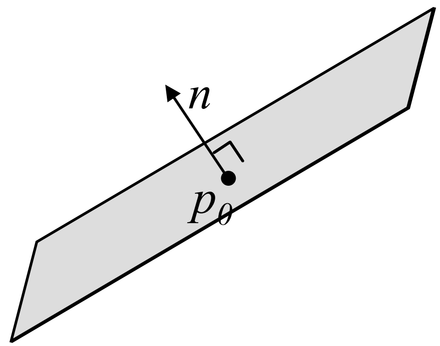
Epoxy Shrinkage shown on the right. Epoxy mounting techniques shown on the left.



Ray Propagation



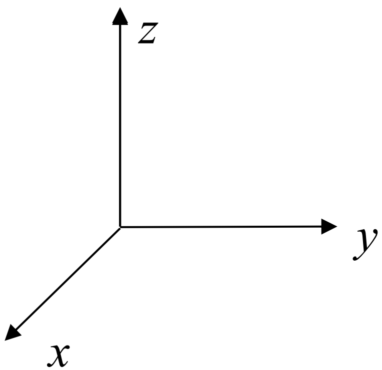
Point l_0 is associated with direction l

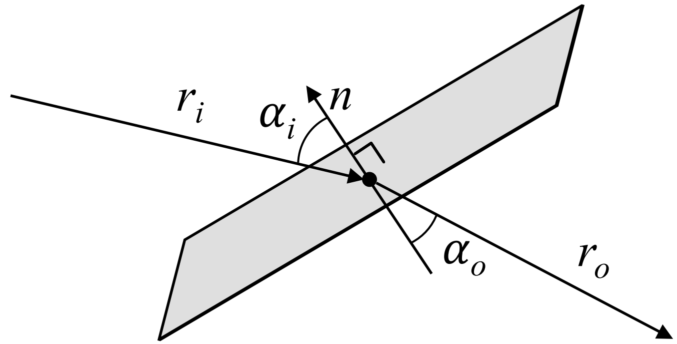


Point p_0 and normal n define a plane

- Line l intersects the plane p at $l_0 + \frac{n \cdot (p_0 - l_0)}{l \cdot p} * l$
- The distance travelled between l_0 and p_0 is $\frac{n \cdot (p_0 - l_0)}{l \cdot p} * ||l||$

Snell's Law in 3 dimensions





This reduces to Snell's Law in 2 dimensions if we transform coordinates such that our new *x* and *y* lie in the plane formed by r_i and *n*. The equations are shown below

$$T = \begin{pmatrix} \hat{n} & v & n \times v \end{pmatrix}, \qquad v = -(r_i - \hat{r_i} \cdot (-n))$$

$$R = \begin{pmatrix} \cos(\Delta\alpha) & \sin(\Delta\alpha) & 0 \\ -\sin(\Delta\alpha) & \cos(\Delta\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

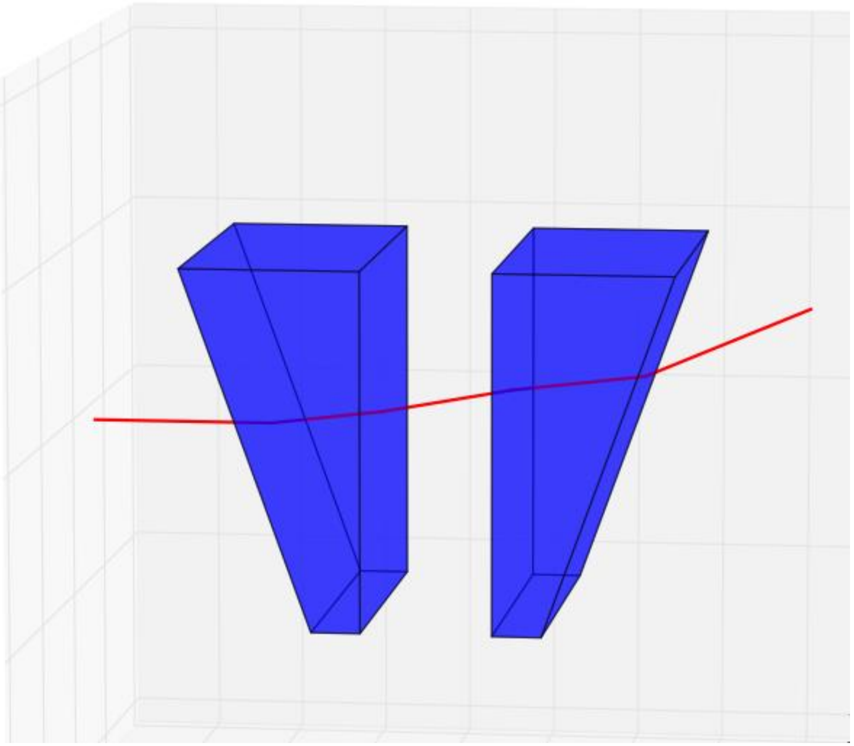
$$\Delta\alpha = \alpha_o - \alpha_i = \sin^{-1}\left(\frac{n_i}{n_o}\sin(\alpha_i)\right) - \alpha_i$$

$$\alpha_i = \cos^{-1}\left(\frac{r_i \cdot n}{||r_i|| \cdot ||n||}\right)$$

$$\boxed{r_o = T \cdot R \cdot T^{-1} r_i}$$

Ray Propagation

By propagating in between prism faces and through material interfaces we can trace the ray path



Ray Propagation

Topographic Map

$$R = r - e - n(d'_1 + d'_2) - \frac{d_p}{\cos \beta_{1_o}}$$

$$P_{xyz} = R \cdot l_{2_o} + p_{2_o}$$

$$P_n = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} P_{xyz}$$

$$\boxed{P = \mathrm{DCM}_{\mathrm{IMU}} \cdot P_n + \begin{pmatrix} 0 \\ 0 \\ 15\cos(20^\circ) \end{pmatrix}}$$

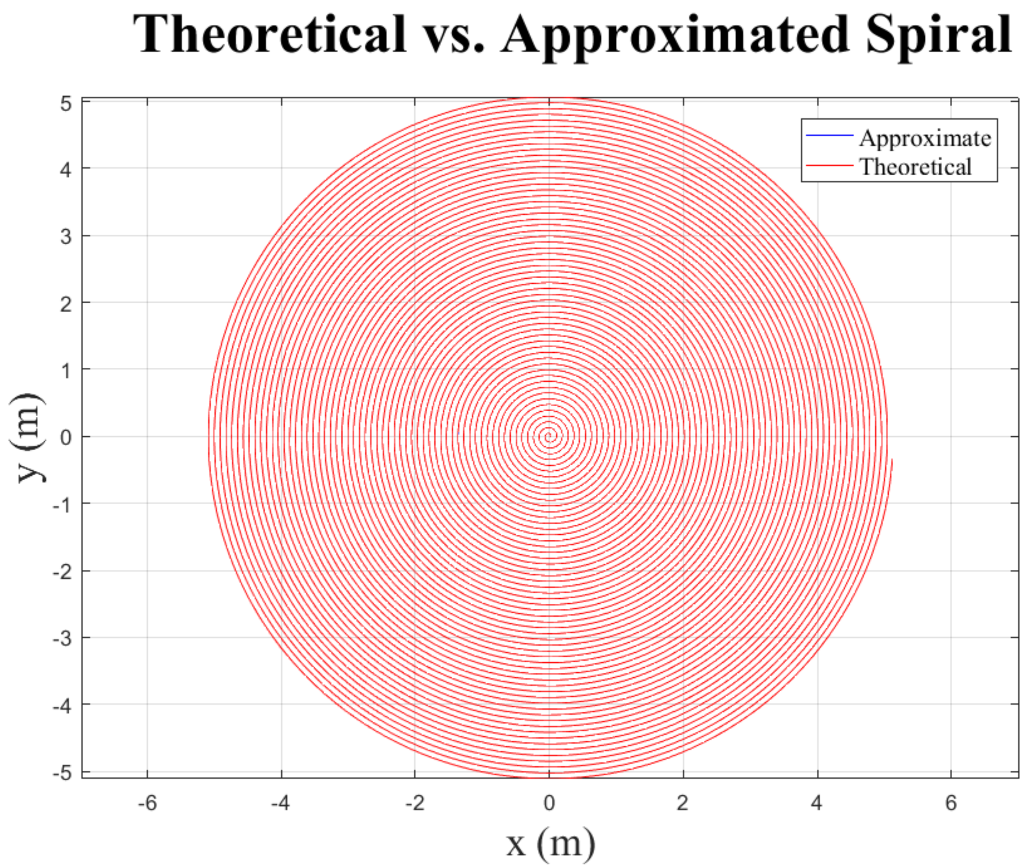
r	Lidar return
e	Distance between lidar and first prism
d_p	Prism separation
n	Prism refractive index
d'	Distance travelled within prism
l	Direction vector
p	Position vector
β	Angle between beam and optical axis

Scan Pattern to Prism Angles

- Radial component of points determined by prism offset angle

- Once offset angle is determined, theta component is found by rotating prisms together

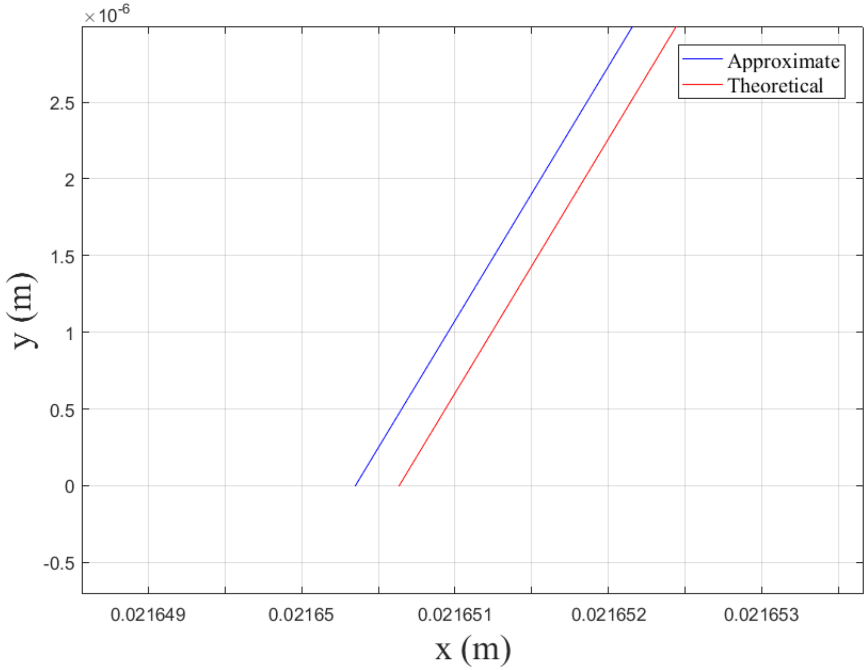
- Prism angles can be found numerically for all points in scan



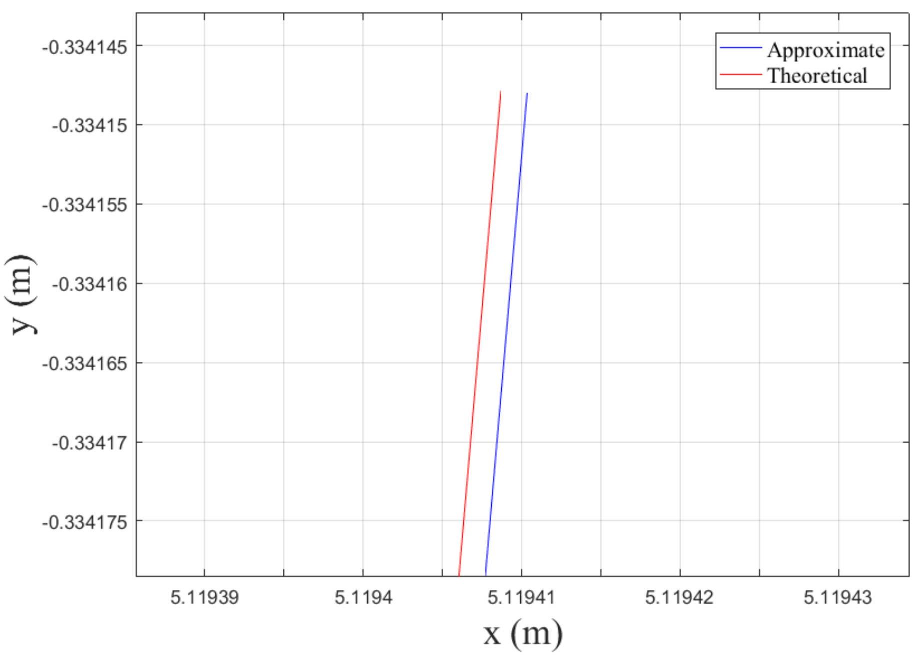
Scan Pattern Approximation

Time Scan:

Scan Center:



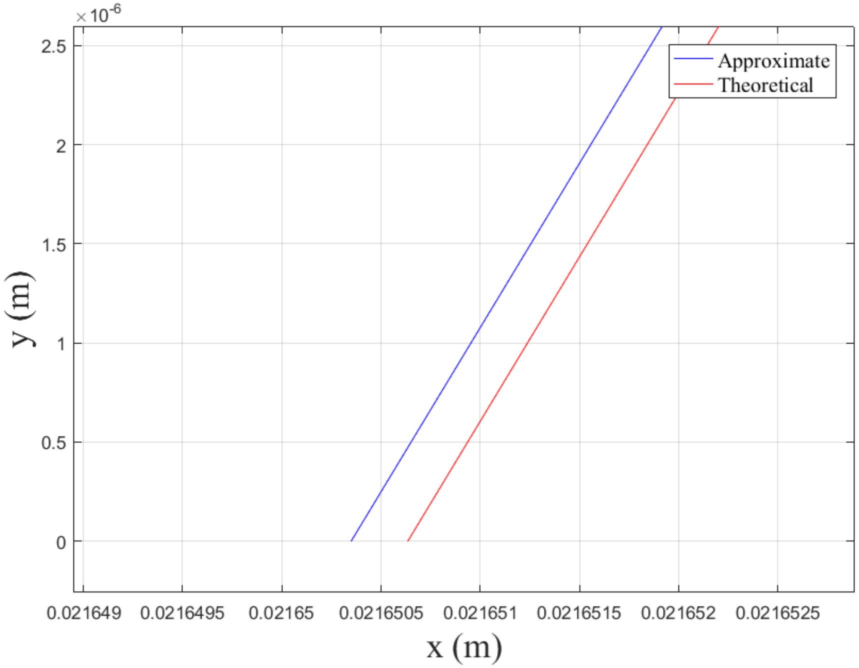
Scan Edge:



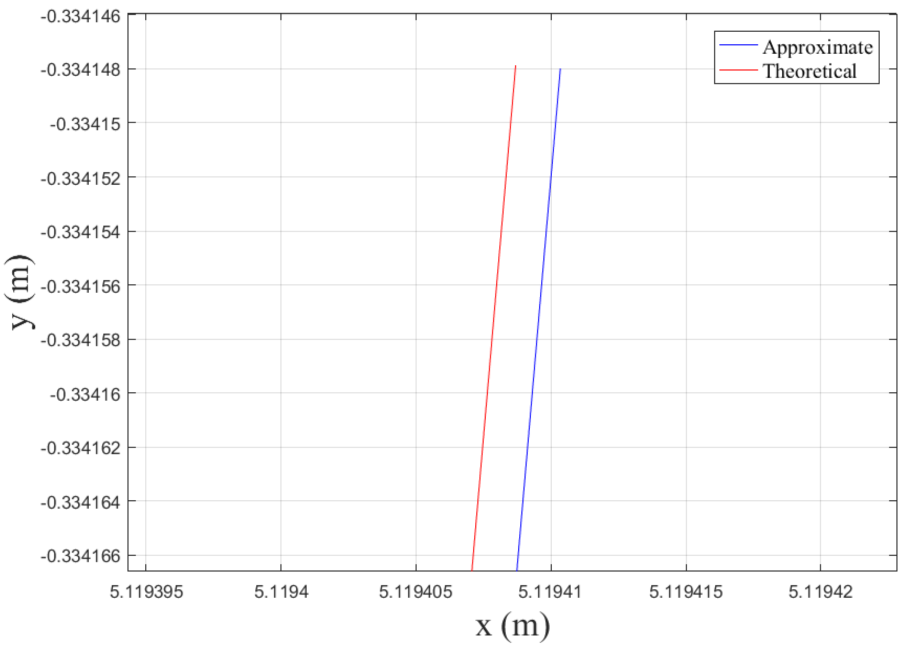
Scan Pattern Approximation

Resolution Scan:

Scan Center:

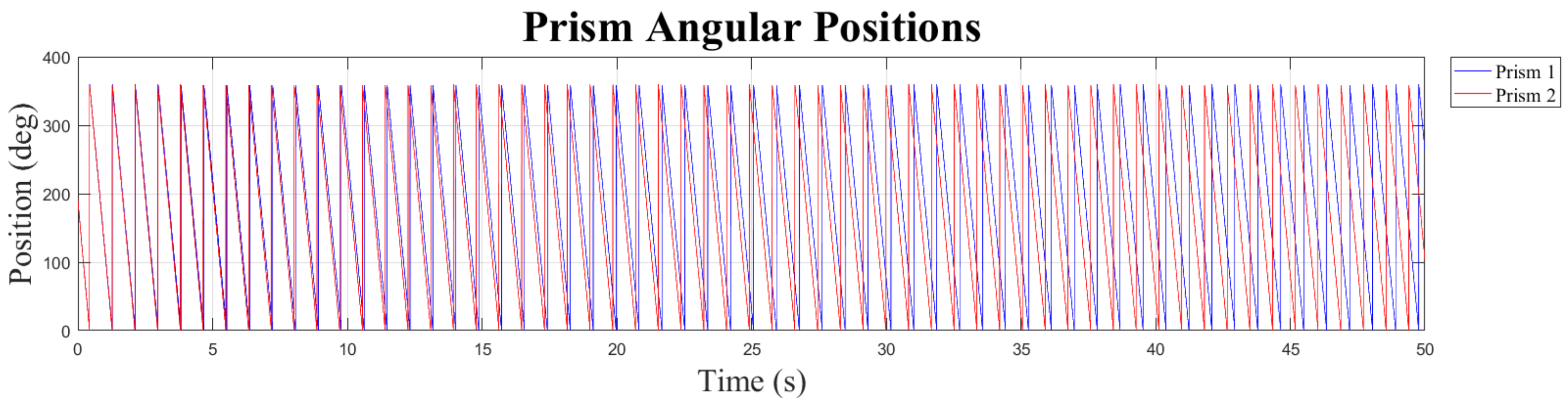


Scan Edge:

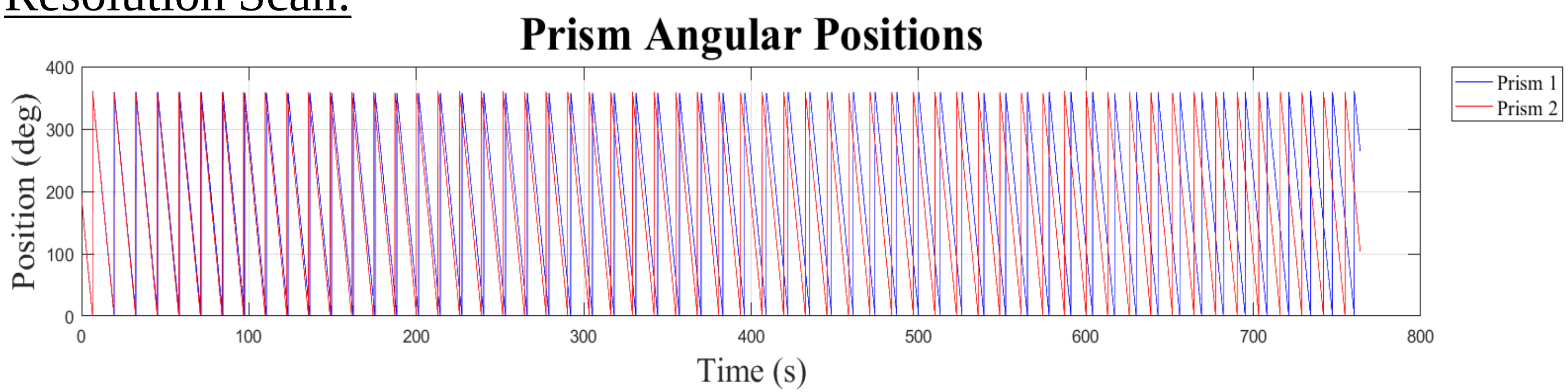


Prism Positions

Time Scan:



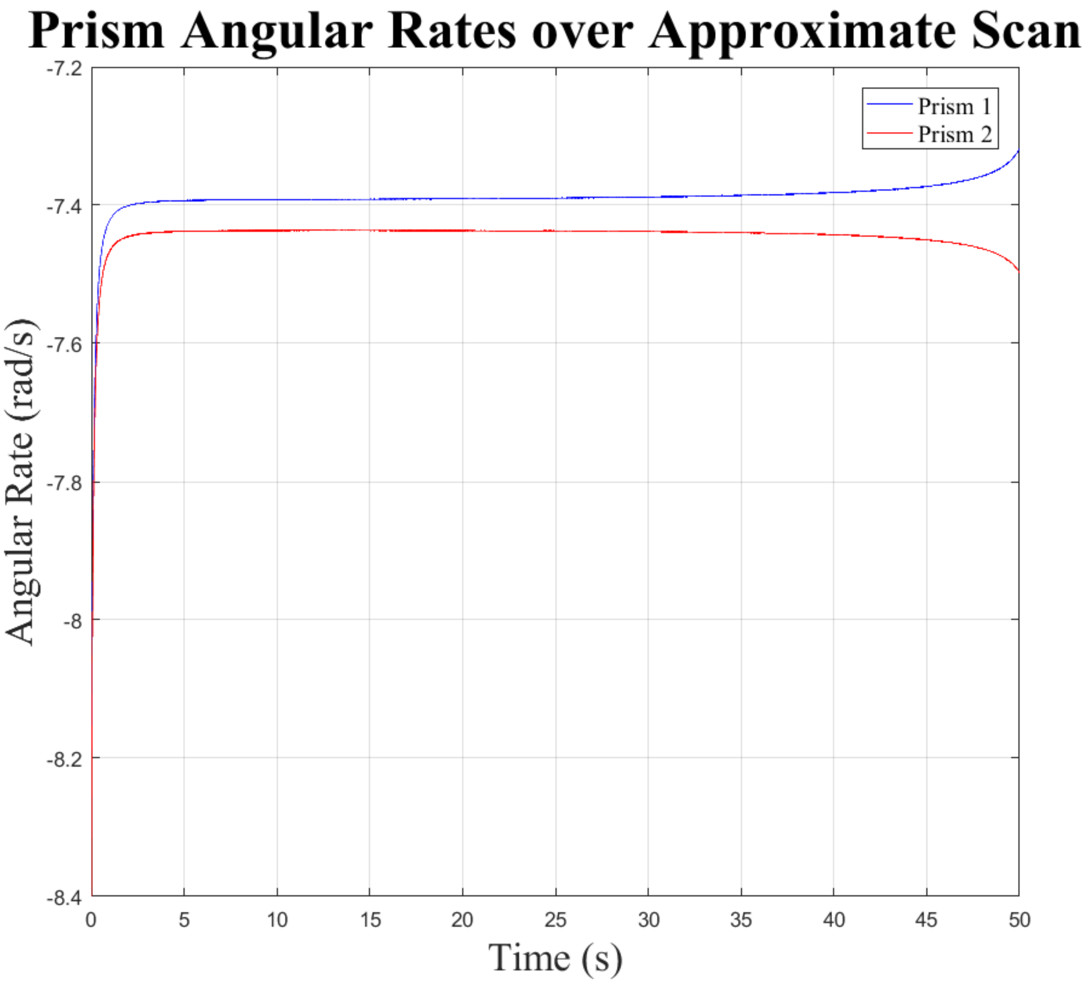
Resolution Scan:



Motor Rates

<u>Time Scan:</u>

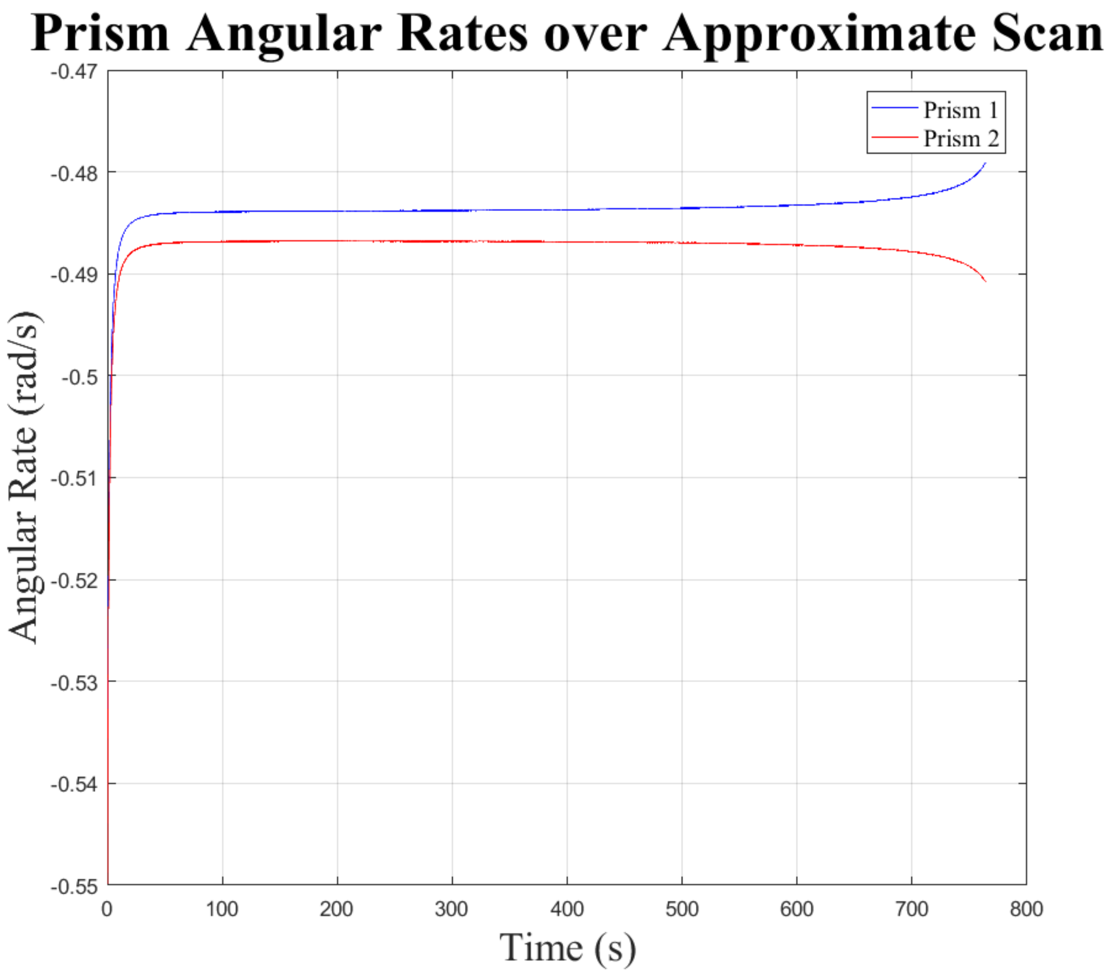
- Min Rate: 7.34 rad/s
- Max Rate: 8.46 rad/s
- Max Accel: 14.36 rad/s²



Motor Rates

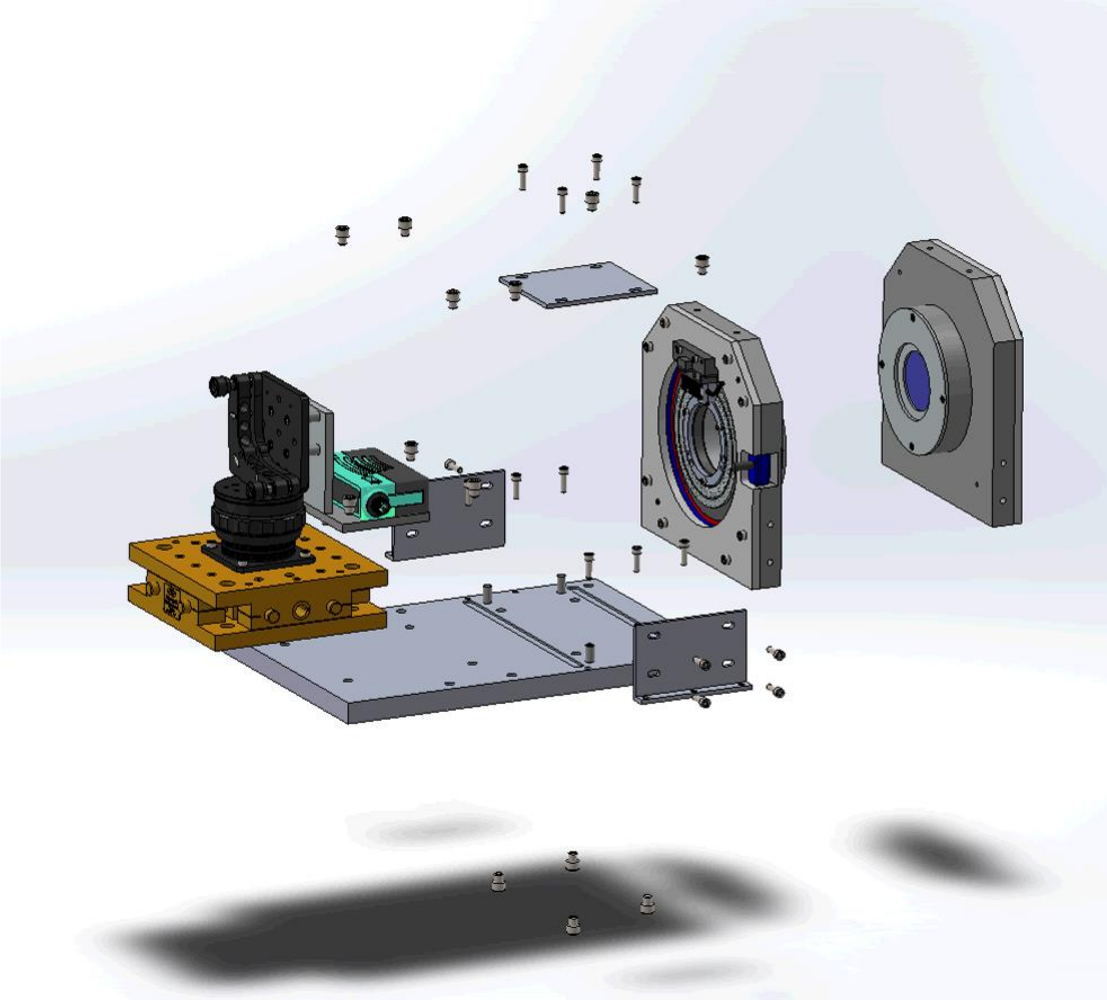
Resolution Scan:

- Min Rate: 0.48 rad/s
- Max Rate: 0.55 rad/s
- Max Accel: 0.047 rad/s²

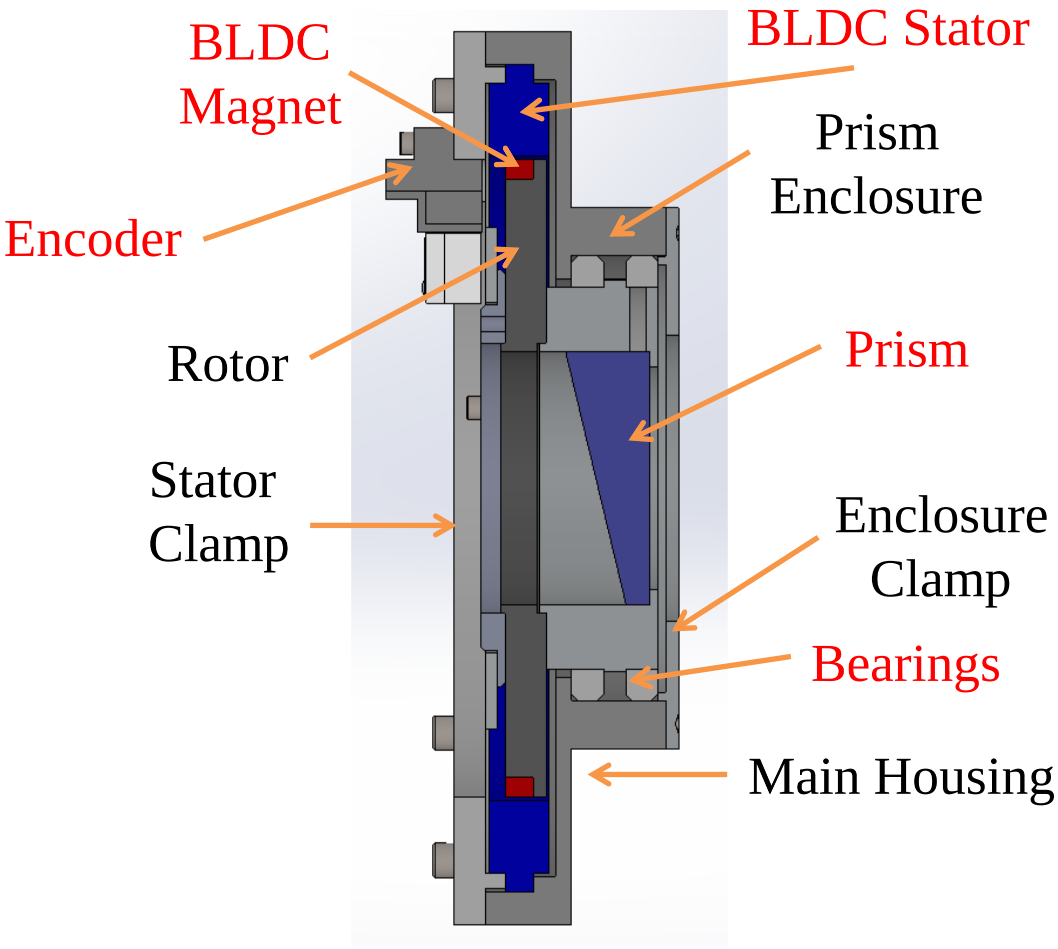


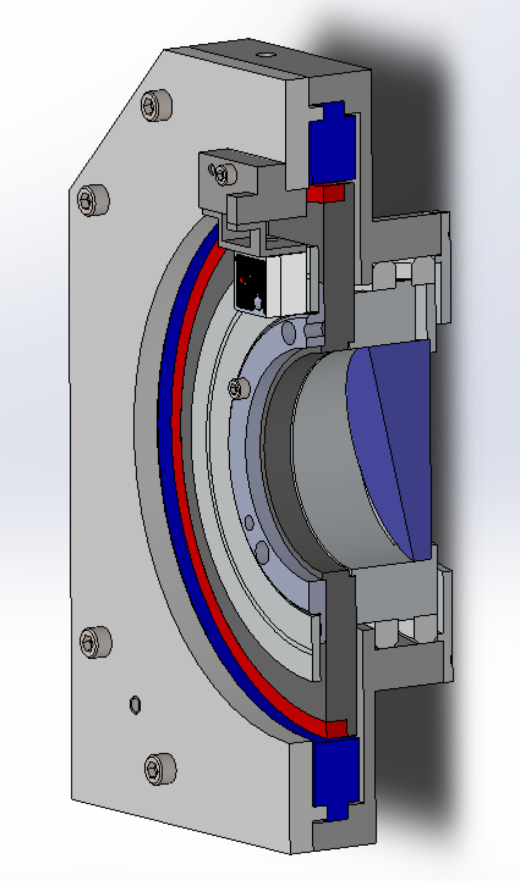
BACKUP: SYSTEM ASSEMBLY

Movie

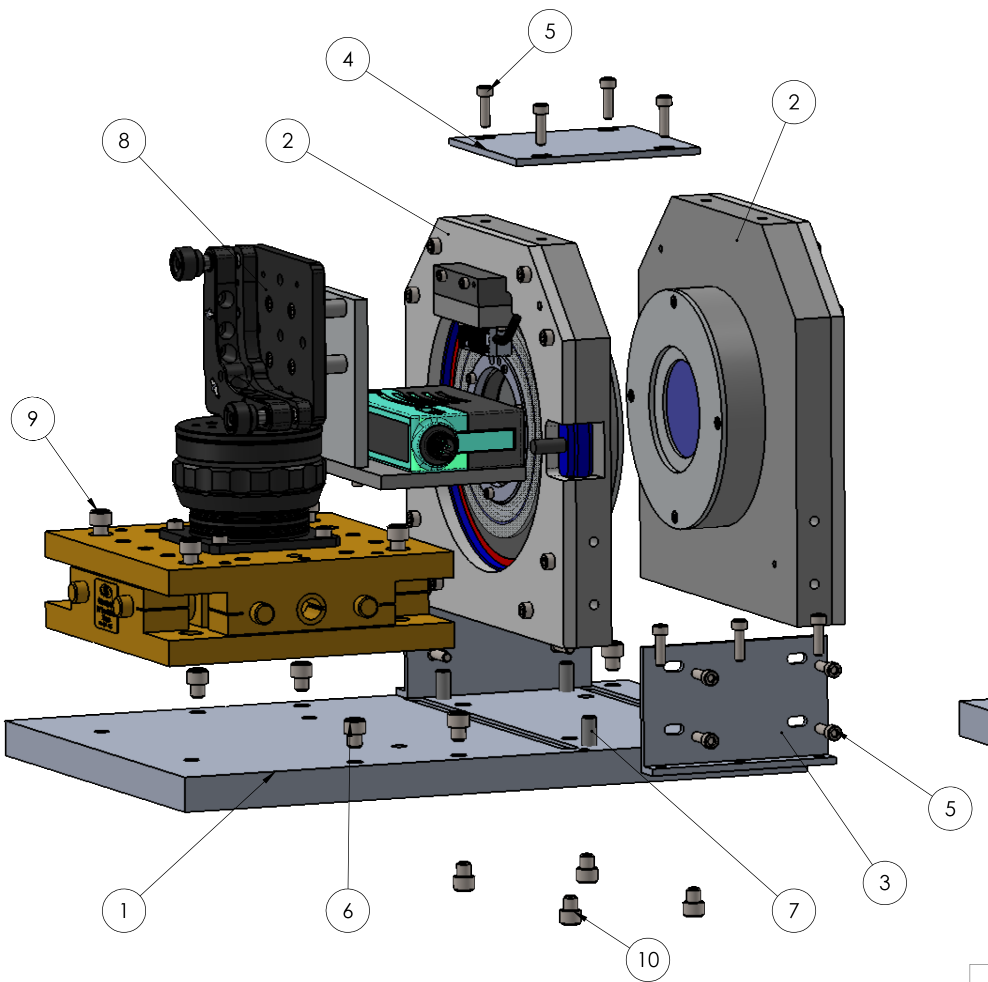


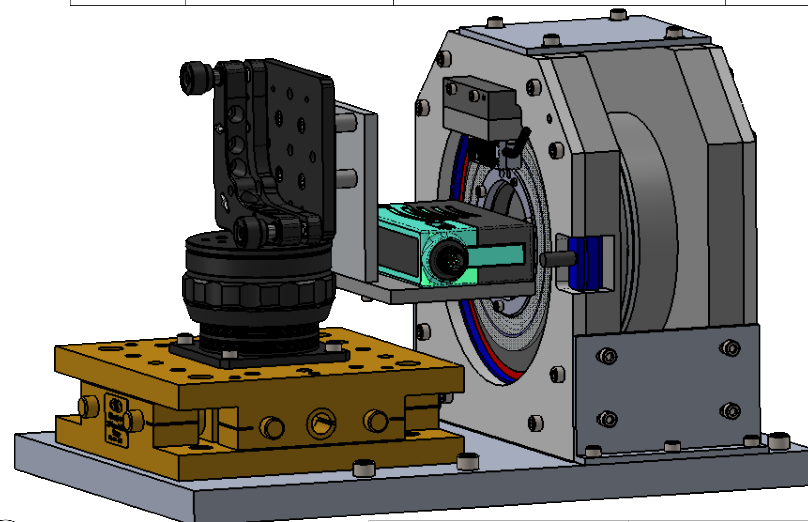
Scanning Stage





ITEM NO.	PART NUMBER	DESCRIPTION	Default/ QTY.
1	0PRT0014	SCN, Baseplate	1
2	0ASM0001	SCN, Scanning Stage	2
3	0PRT0012	SCN, Side Bracket	2
4	0PRT0013	SCN, Top Bracket	1
5	#8-32 X 3/8 SHCS		18
6	1/4 - 20X 1 SHCS		6
7	0PRT0016	SCN, Dowel Pin, 1/4-20	4
8	0ASM0021	SCN, Lidar Assembly	1
9	1/4 - 20 X 5/8 SHCS		4
10	1/4 - 20 X 3/4 SHCS		4





INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH
FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

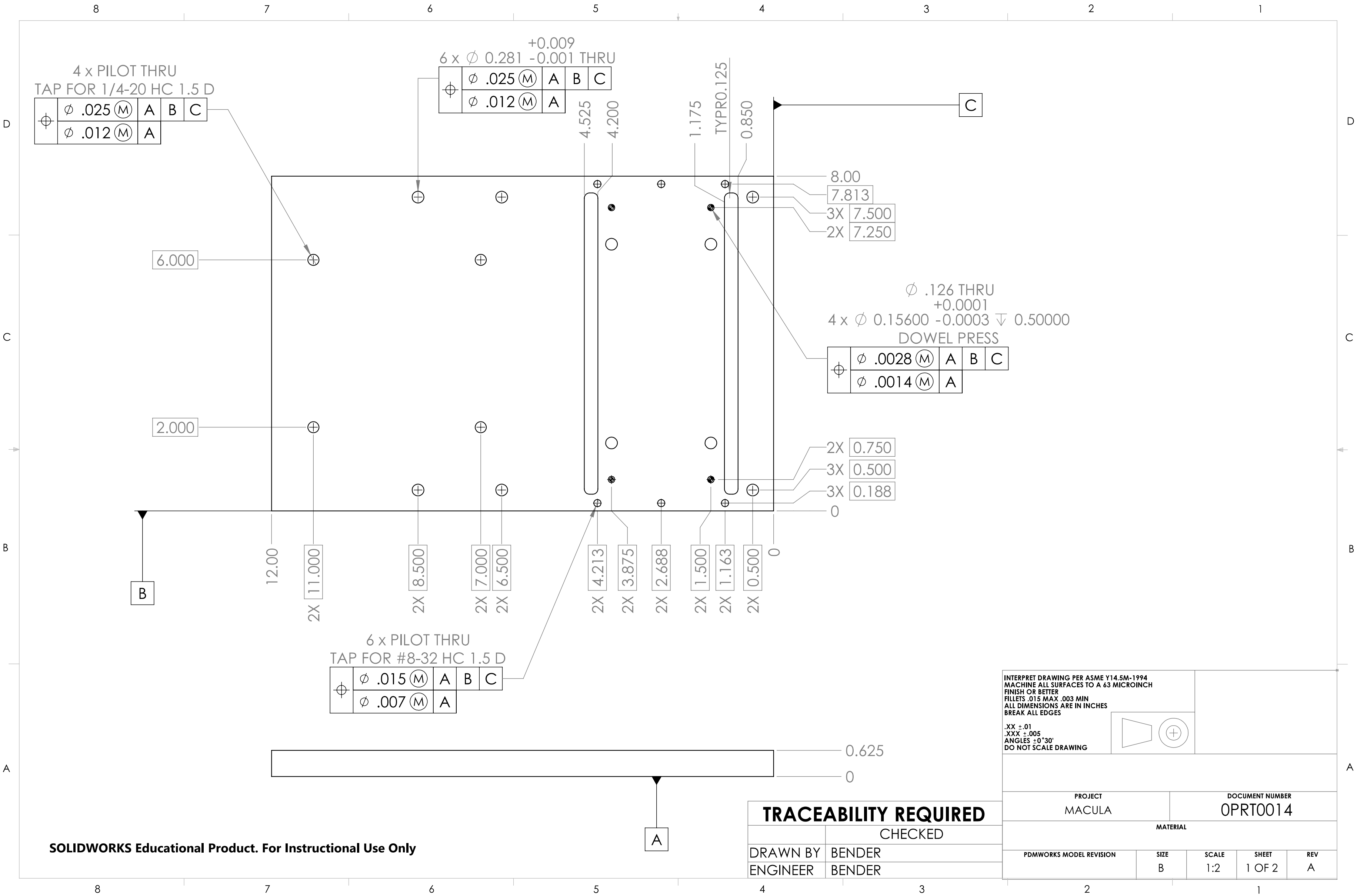
TRACEABILITY REQUIRED

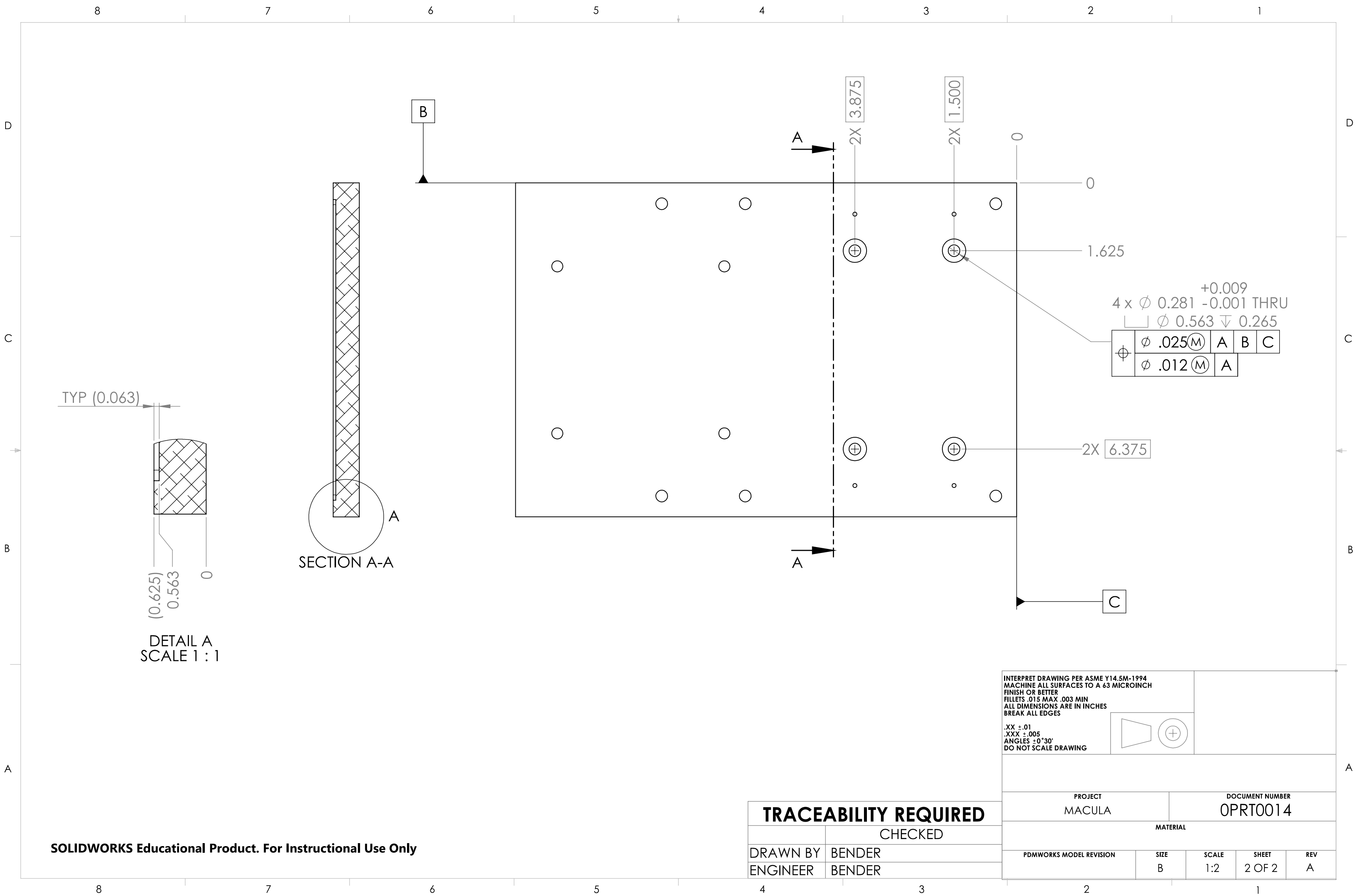
	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

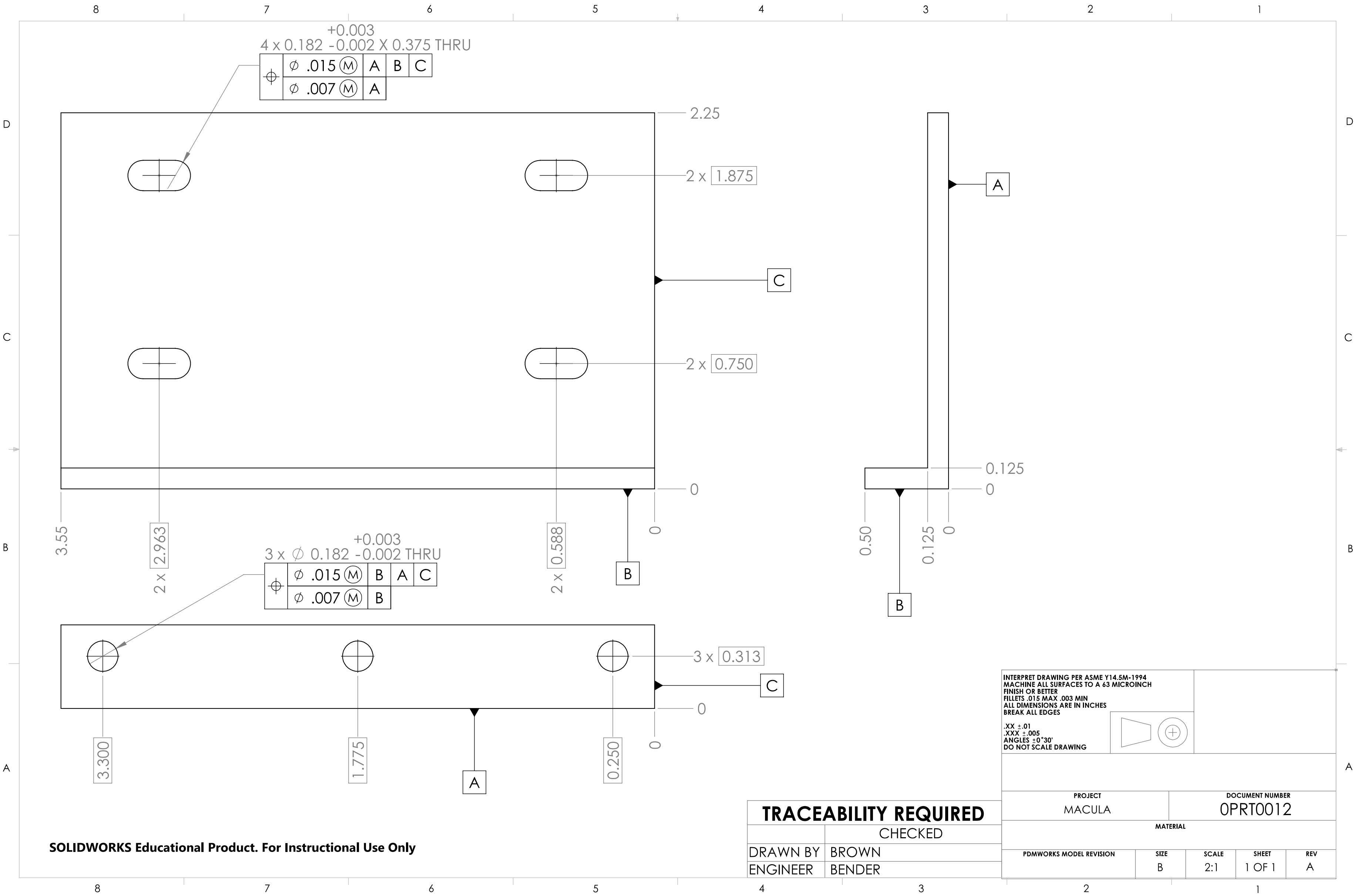
PROJECT	DOCUMENT NUMBER
MACULA	0ASM0015

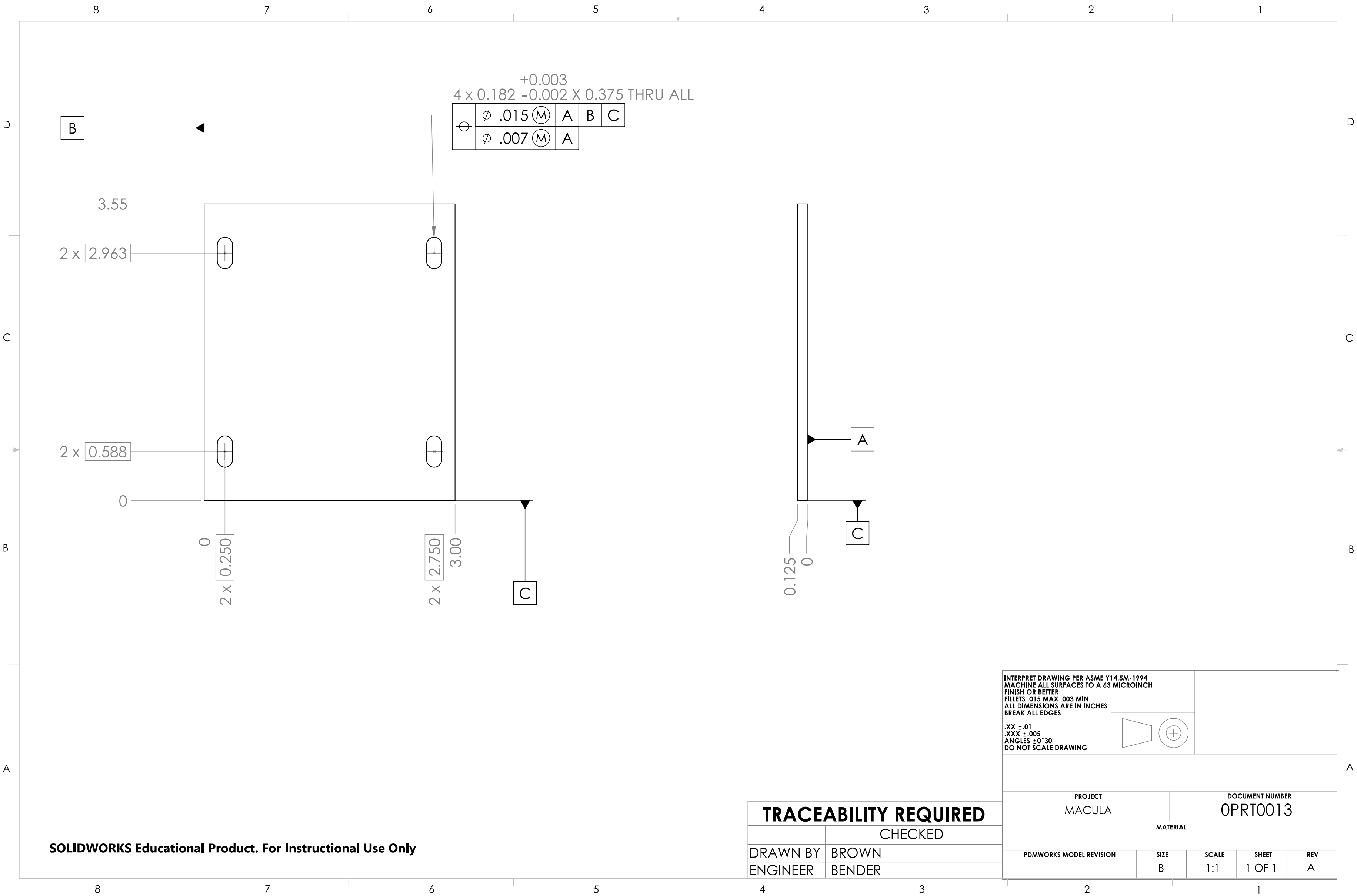
MATERIAL

PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	1:1	1 OF 1	A

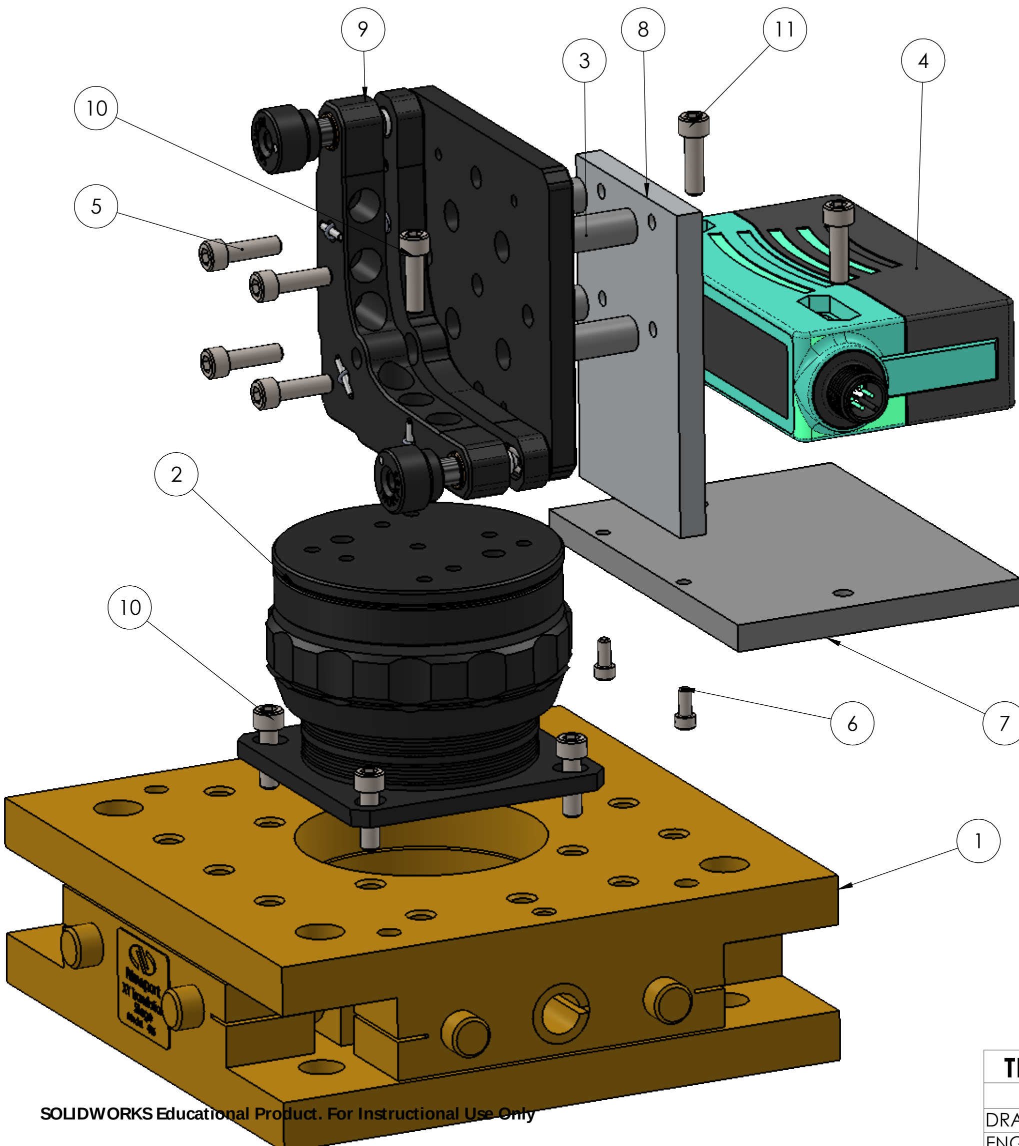

4 x PILOT THRU
TAP FOR 1/4-20 HC 1.5 D
⌖ ∅ .025 Ⓜ A B C
∅ .012 Ⓜ A
+0.009
6 x ∅ 0.281 -0.001 THRU
⌖ ∅ .025 Ⓜ A B C
∅ .012 Ⓜ A
4.525
4.200
1.175
TYPR0.125
0.850
C
8.00
7.813
3X 7.500
2X 7.250
6.000
∅ .126 THRU
+0.0001
4 x ∅ 0.15600 -0.0003 ↧ 0.50000
DOWEL PRESS
⌖ ∅ .0028 Ⓜ A B C
∅ .0014 Ⓜ A
2.000
2X 0.750
3X 0.500
3X 0.188
0
B
12.00
2X 11.000
2X 8.500
2X 7.000
2X 6.500
2X 4.213
2X 3.875
2X 2.688
2X 1.500
2X 1.163
2X 0.500
0
6 x PILOT THRU
TAP FOR #8-32 HC 1.5 D
⌖ ∅ .015 Ⓜ A B C
∅ .007 Ⓜ A
0.625
0
A
SOLIDWORKS Educational Product. For Instructional Use Only
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
PROJECT
MACULA
DOCUMENT NUMBER
0PRT0014
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:2
SHEET 1 OF 2
REV A

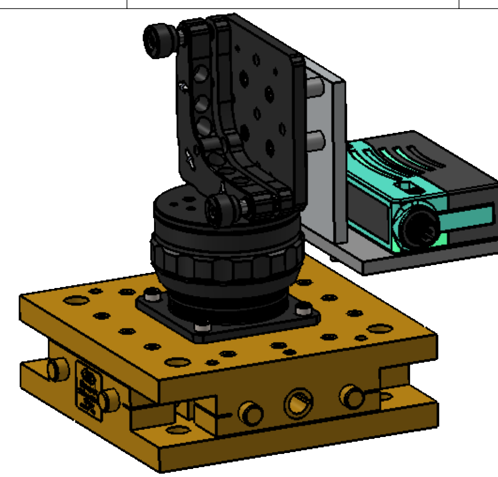

B
A
2X 3.875
2X 1.500
0
0
1.625
4 x ∅ 0.281 +0.009 -0.001 THRU
∅ 0.563 ↧ 0.265
∅ .025 Ⓜ A B C
∅ .012 Ⓜ A
2X 6.375
A
C
TYP (0.063)
(0.625)
0.563
0
DETAIL A
SCALE 1 : 1
A
SECTION A-A
SOLIDWORKS Educational Product. For Instructional Use Only
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH
FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
PROJECT
MACULA
DOCUMENT NUMBER
0PRT0014
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:2
SHEET 2 OF 2
REV A


+0.003
4 x 0.182 -0.002 X 0.375 THRU
∅ .015 Ⓜ A B C
∅ .007 Ⓜ A
2.25
2 x 1.875
2 x 0.750
0
A
C
0.125
0
3.55
2 x 2.963
2 x 0.588
0
B
0.50
0.125
0
B
+0.003
3 x ∅ 0.182 -0.002 THRU
∅ .015 Ⓜ B A C
∅ .007 Ⓜ B
3 x 0.313
C
0
3.300
1.775
A
0.250
0
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BROWN
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0012
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 2:1
SHEET 1 OF 1
REV A
SOLIDWORKS Educational Product. For Instructional Use Only


+0.003
4 x 0.182 -0.002 X 0.375 THRU ALL
⌀ .015 Ⓜ A B C
⌀ .007 Ⓜ A
B
3.55
2 x 2.963
2 x 0.588
0
0
2 x 0.250
2 x 2.750
3.00
C
A
C
0.125
0
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH
FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BROWN
ENGINEER BENDER
PROJECT
MACULA
DOCUMENT NUMBER
0PRT0013
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:1
SHEET 1 OF 1
REV A
SOLIDWORKS Educational Product. For Instructional Use Only

ITEM NO.	PART NUMBER	DESCRIPTION	Default/ QTY.
1	SCN, XY Stage, Newport 406	COTS LINEAR STAGE	1
2	SCN, Z stage, Newport 488	COTS HEIGHT ADJUSTMENT	1
3	92510A567	SPACER	4
4	VDM28	LIDAR	1
5	# 8- 32 X 3/8 SHCS	TBD LENGTH	5
6	# 4-40 X 7/16 SHCS	TBD LENGTH	2
7	0PRT0011	SCN, Lidar Plate	1
8	0PRT0020	SCN, Lidar Bracket	1
9	KM200B	TILT STAGE	1
10	# 8- 32 X 1.00 SHCS		4
11	# 8- 32 X 1.125 SHCS		2





INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

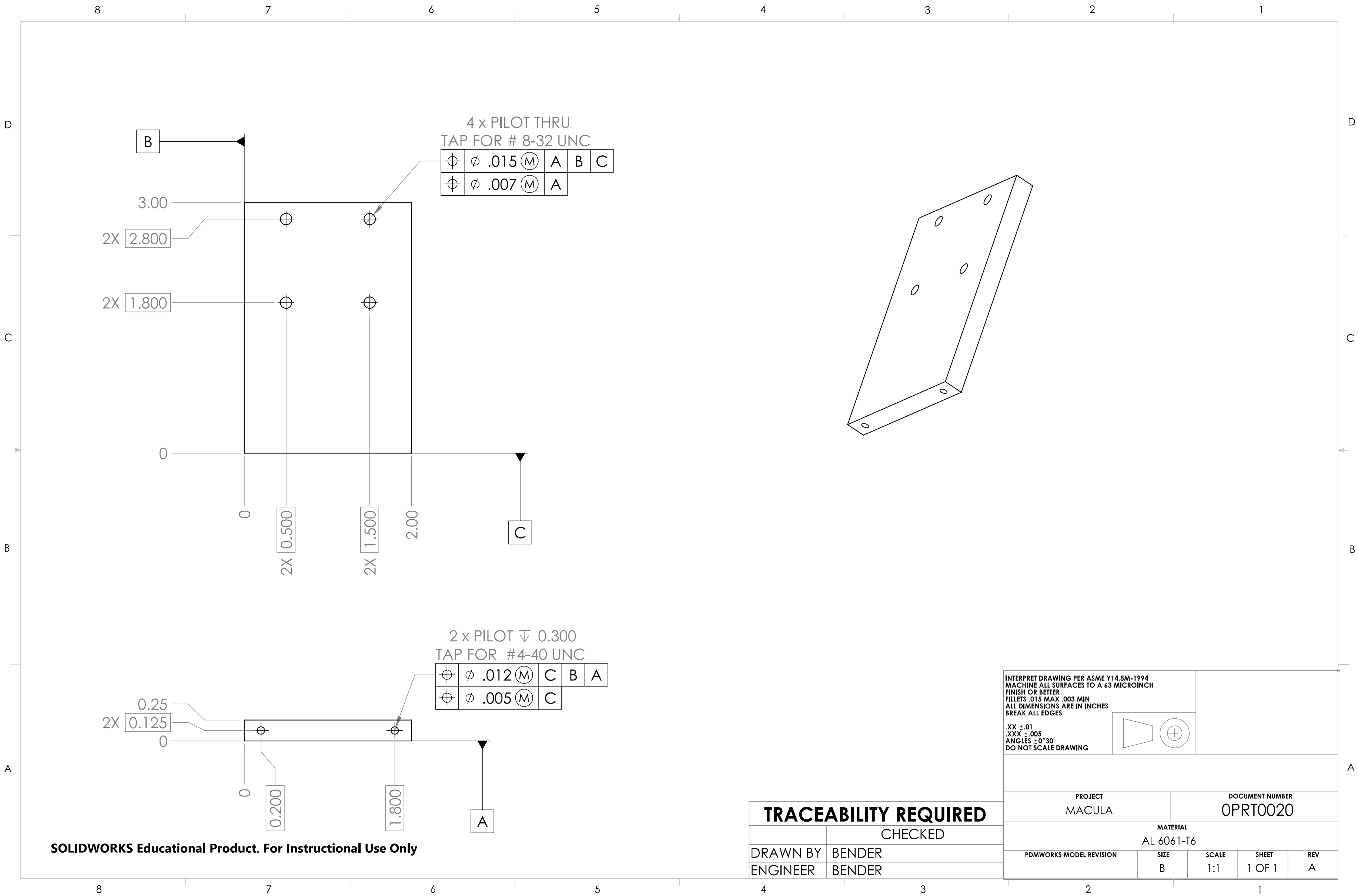
TRACEABILITY REQUIRED

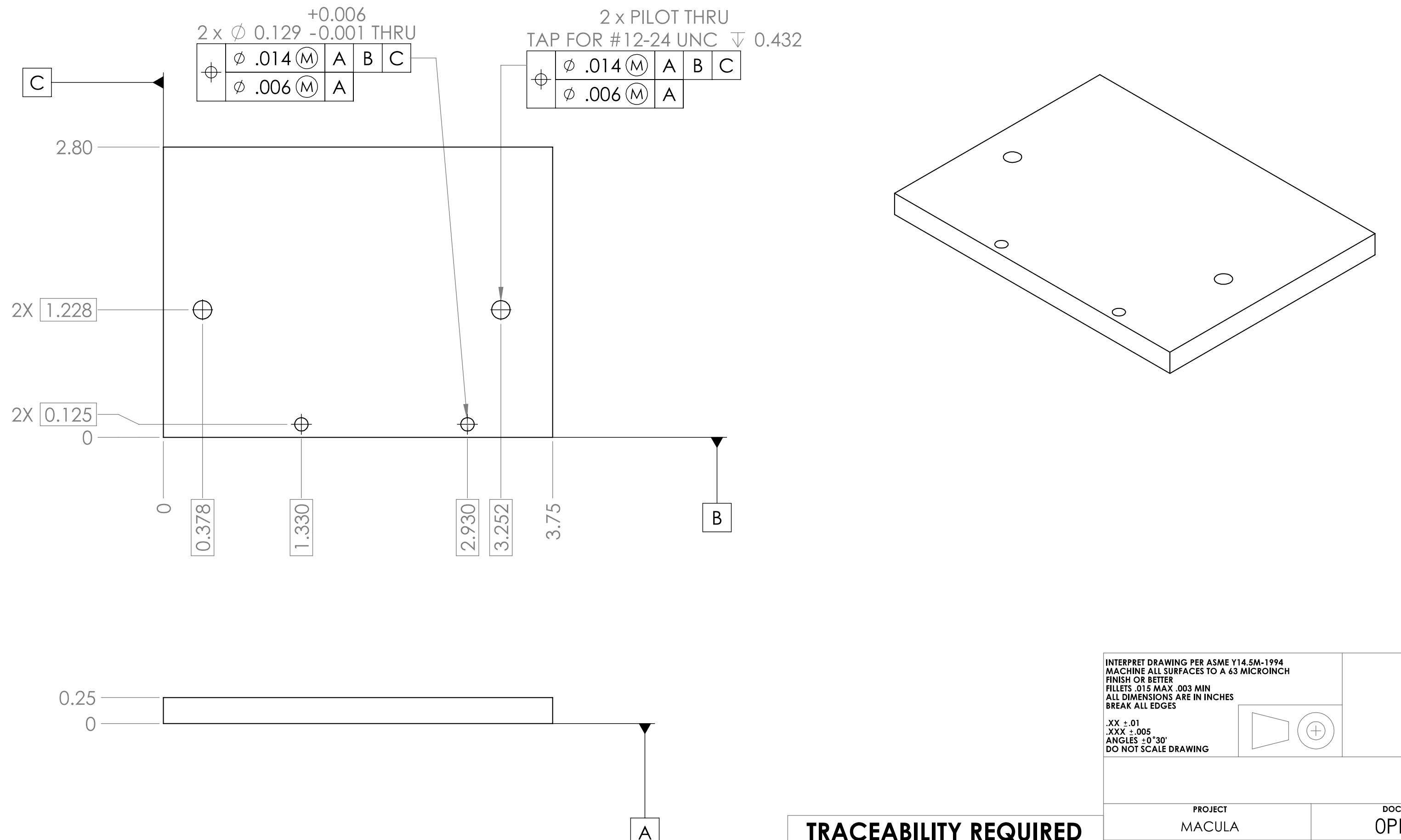
	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

PROJECT	DOCUMENT NUMBER
MACULA	0ASM0021

MATERIAL

PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	1:1	1 OF 1	A


4 x PILOT THRU
TAP FOR # 8-32 UNC
⌖ ∅ .015 Ⓜ A B C
⌖ ∅ .007 Ⓜ A
B
3.00
2X 2.800
2X 1.800
0
0
2X 0.500
2X 1.500
2.00
C
2 x PILOT ↧ 0.300
TAP FOR #4-40 UNC
⌖ ∅ .012 Ⓜ C B A
⌖ ∅ .005 Ⓜ C
0.25
2X 0.125
0
0
0.200
1.800
A
SOLIDWORKS Educational Product. For Instructional Use Only
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0020
MATERIAL AL 6061-T6
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:1
SHEET 1 OF 1
REV A



INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

PROJECT	DOCUMENT NUMBER
MACULA	0PRT0011

MATERIAL

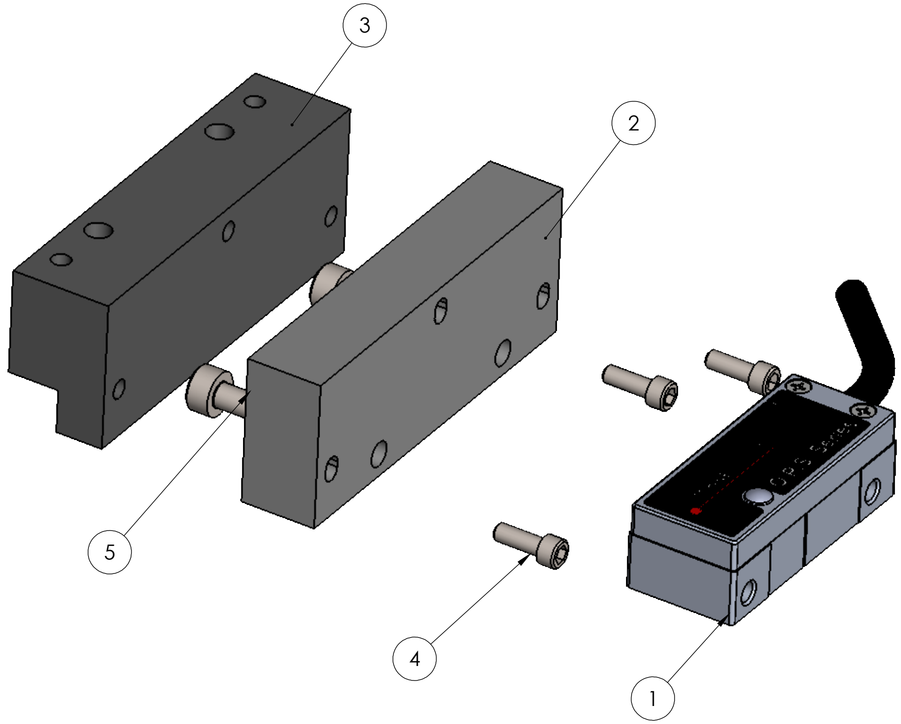
PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	1:1	1 OF 1	A

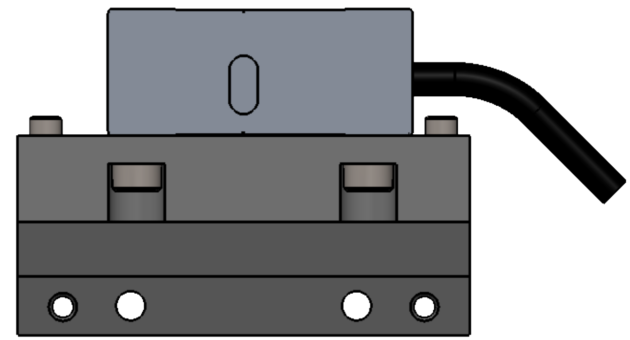
TRACEABILITY REQUIRED

	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

SOLIDWORKS Educational Product. For Instructional Use Only

ITEM NO.	PART NUMBER	DESCRIPTION	Default/ QTY.
1	SCN, ops-sm-020-3-1	CELERA OPS ENCODER	1
2	0PRT0017		1
3	0PRT0018		1
4	HX-SHCS #2-56 X 9/16 UNC		3
5	HX-SHCS M 3 X14 mm		2





INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

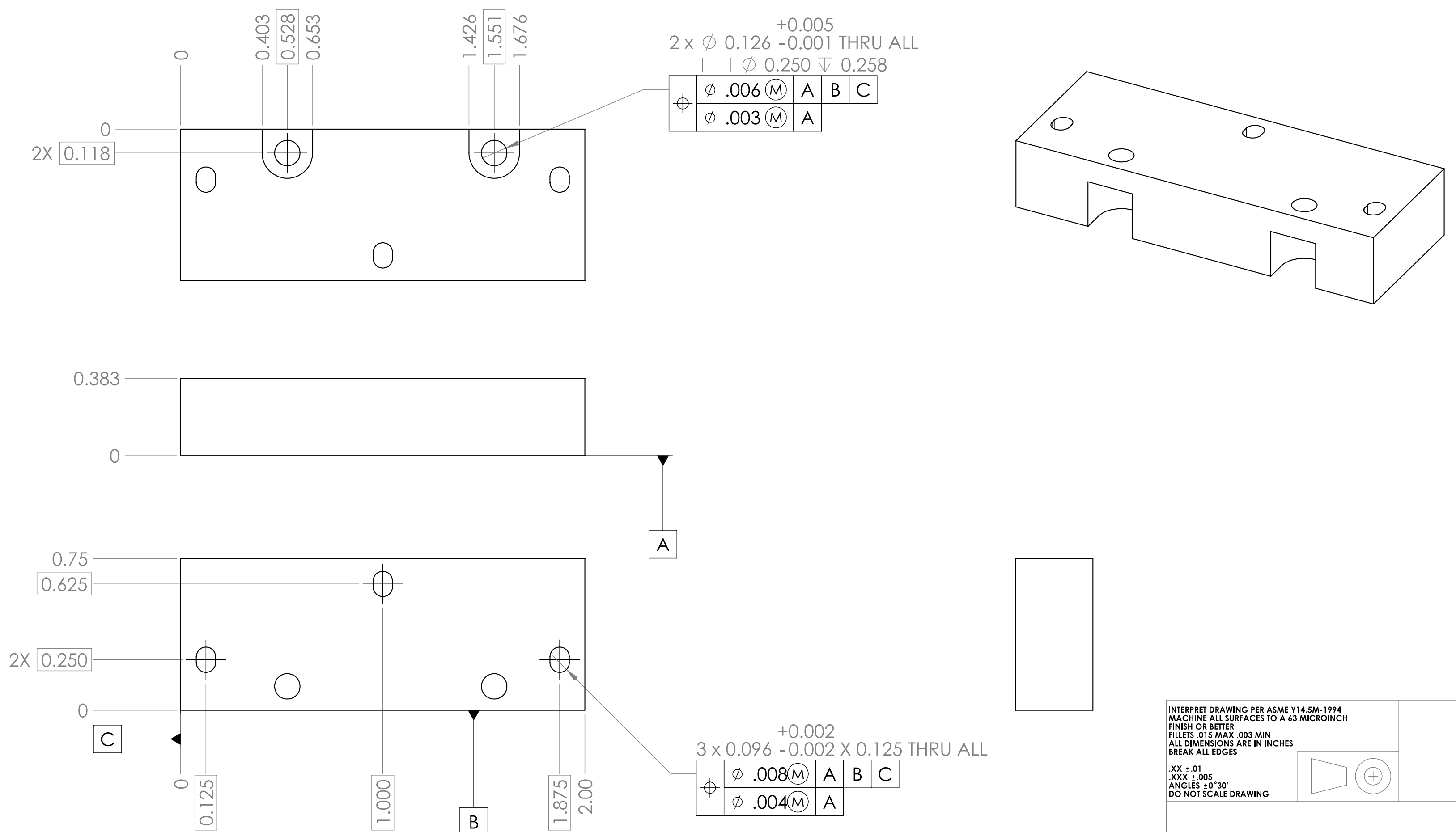
TRACEABILITY REQUIRED

	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

PROJECT	DOCUMENT NUMBER
MACULA	0ASM0019

MATERIAL: AS REQUIRED

PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	2:1	1 OF 1	A



INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

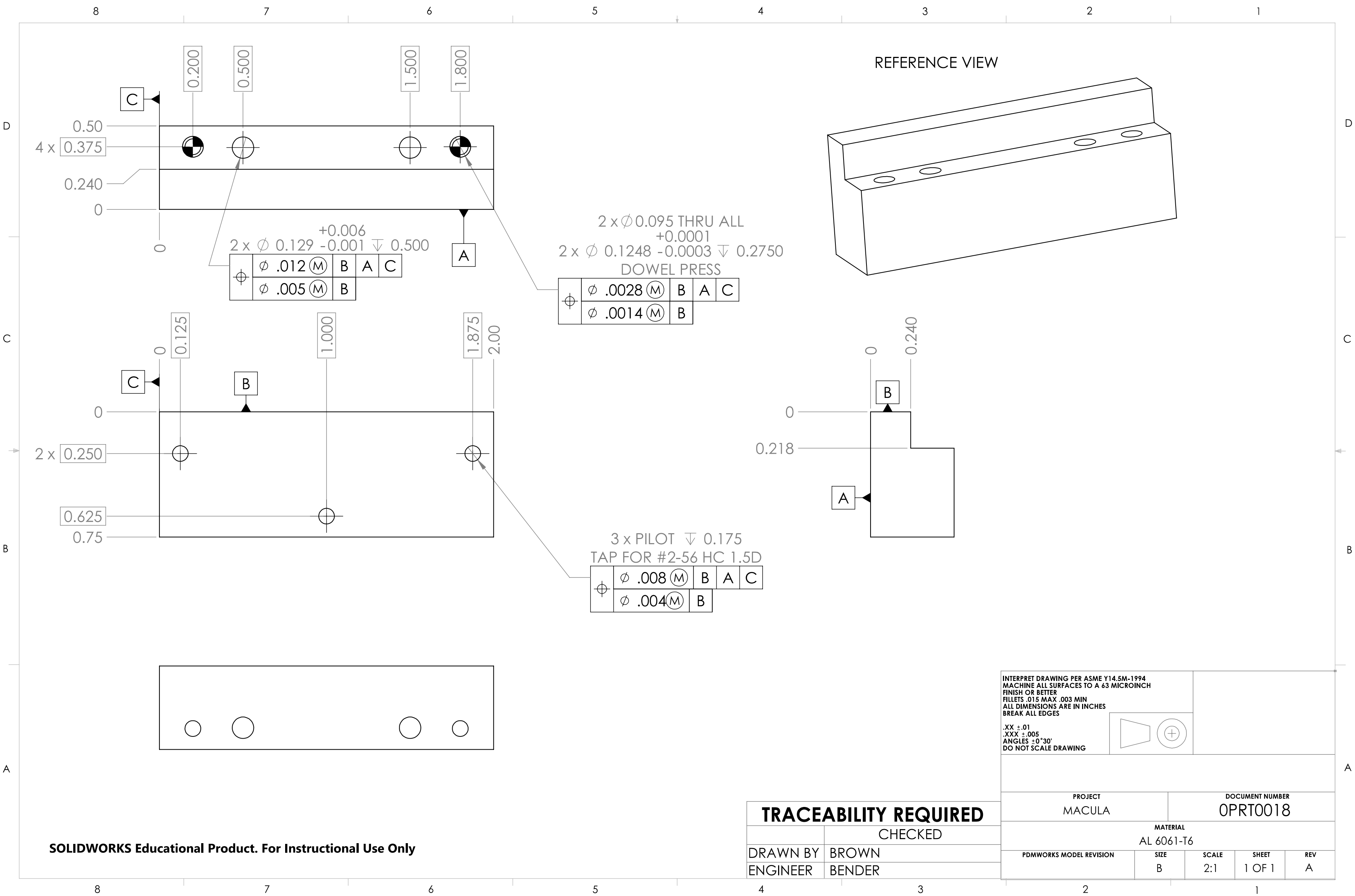
TRACEABILITY REQUIRED

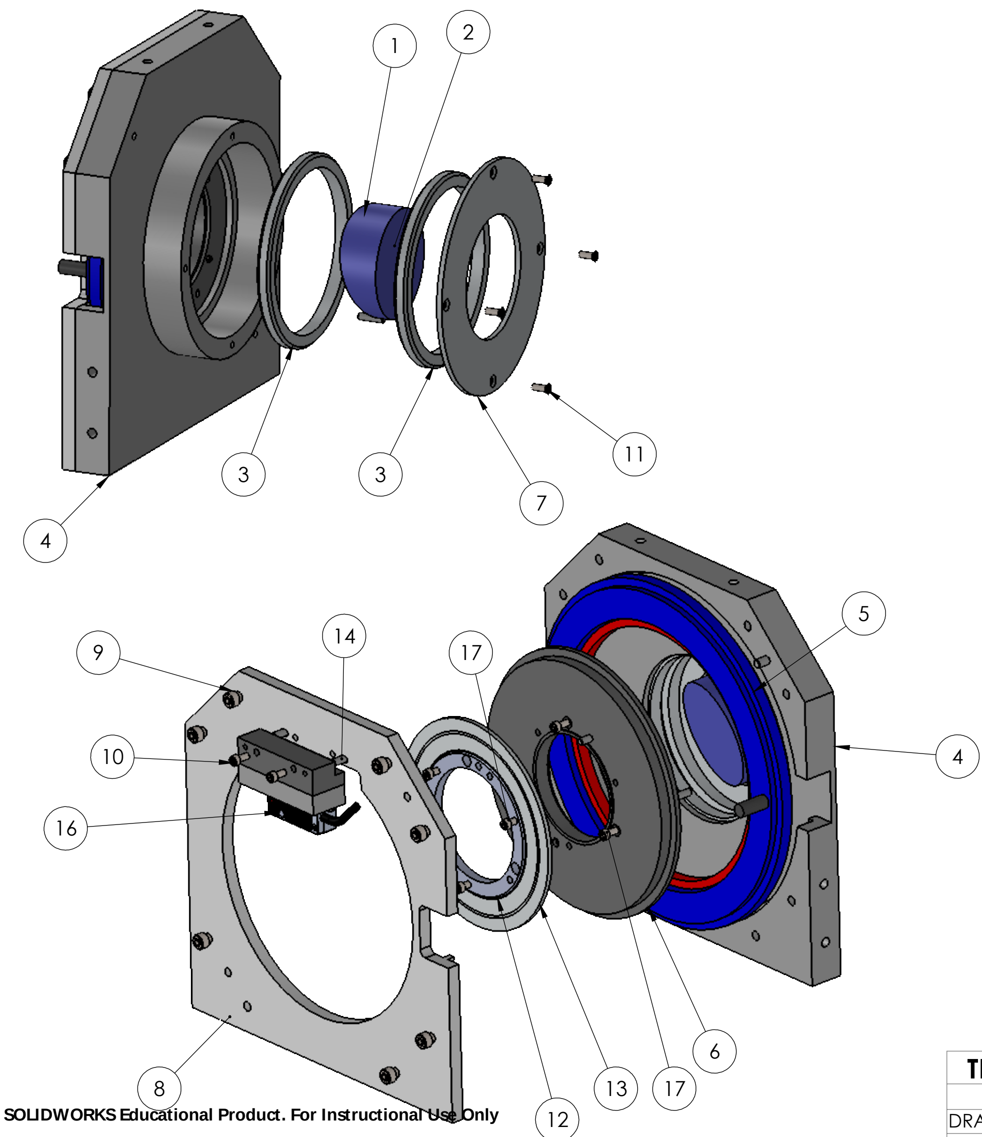
	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

PROJECT	DOCUMENT NUMBER
MACULA	0PRT0017revB

MATERIAL
AL 6061-T6

PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	2:1	1 OF 1	A


REFERENCE VIEW
0.200
0.500
1.500
1.800
0.50
4 x 0.375
0.240
0
2 x ∅ 0.129 +0.006 -0.001 ↧ 0.500
∅ .012 Ⓜ B A C
∅ .005 Ⓜ B
2 x ∅0.095 THRU ALL
2 x ∅ 0.1248 +0.0001 -0.0003 ↧ 0.2750
DOWEL PRESS
∅ .0028 Ⓜ B A C
∅ .0014 Ⓜ B
0.125
1.000
1.875
2.00
2 x 0.250
0.625
0.75
0.218
3 x PILOT ↧ 0.175
TAP FOR #2-56 HC 1.5D
∅ .008 Ⓜ B A C
∅ .004 Ⓜ B
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BROWN
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0018
MATERIAL AL 6061-T6
PDMWORKS MODEL REVISION
SIZE B
SCALE 2:1
SHEET 1 OF 1
REV A
SOLIDWORKS Educational Product. For Instructional Use Only



ITEM NO.	PART NUMBER	DESCRIPTION	Default/ QTY.
1	0PRT0003	SCN, Prism Enclosure	1
2	0PRT0009	SCN, Prism	1
3	0PRT0010	SCN, Bearing	2
4	0PRT0002	SCN, Scanning Stage, Main Housing	1
5	ult-165-a-12-a-n-001	BLDC Motor	1
6	0PRT0004	SCN, Rotor	1
7	0PRT0006	SCN, Bearing Clamp	1
8	0PRT0007	SCN, Motor Clamp	1
9	# 8-32 X .5625 SHCS		8
10	#4-40 X .75 SHCS		2
11	#4-40 X.3125 FLATHEAD		4
12	0PRT0005	SCN, Encoder Hub	1
13	0PRT0008	SCN, Encoder Glass Scale	1
14	0PRT0016	SCN, Dowel Pin	4
15	0PRT0016	SCN, Dowel Pin	2
16	0ASM0019	SCN, Encoder Assembly	1
17	#4-40 X .375 SHCS		6

INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

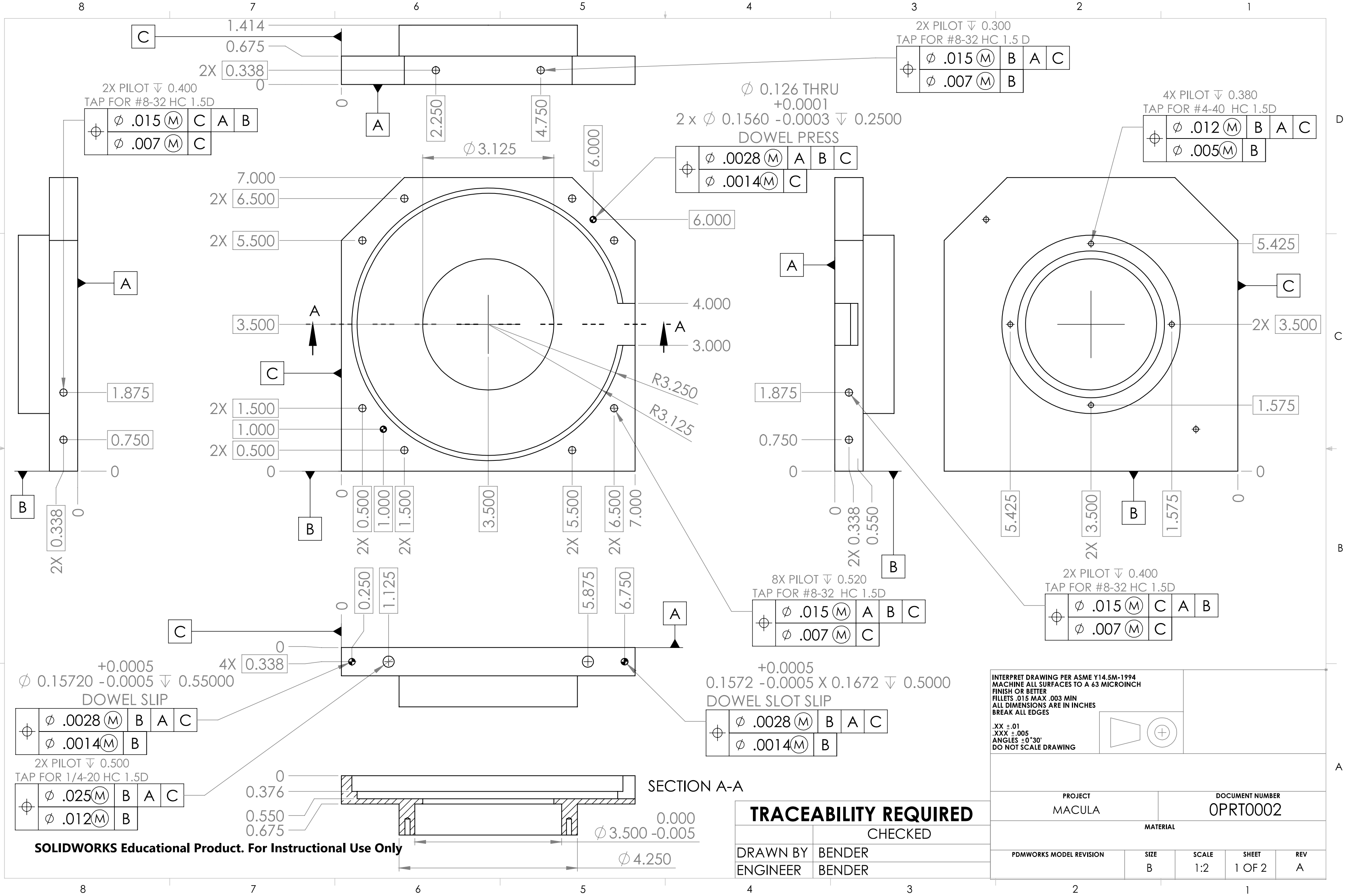
TRACEABILITY REQUIRED

	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

PROJECT	DOCUMENT NUMBER
MACULA	0ASM0001

MATERIAL

PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	1:5	1 OF 1	A



TRACEABILITY REQUIRED

	CHECKED
DRAWN BY	BENDER
ENGINEER	BENDER

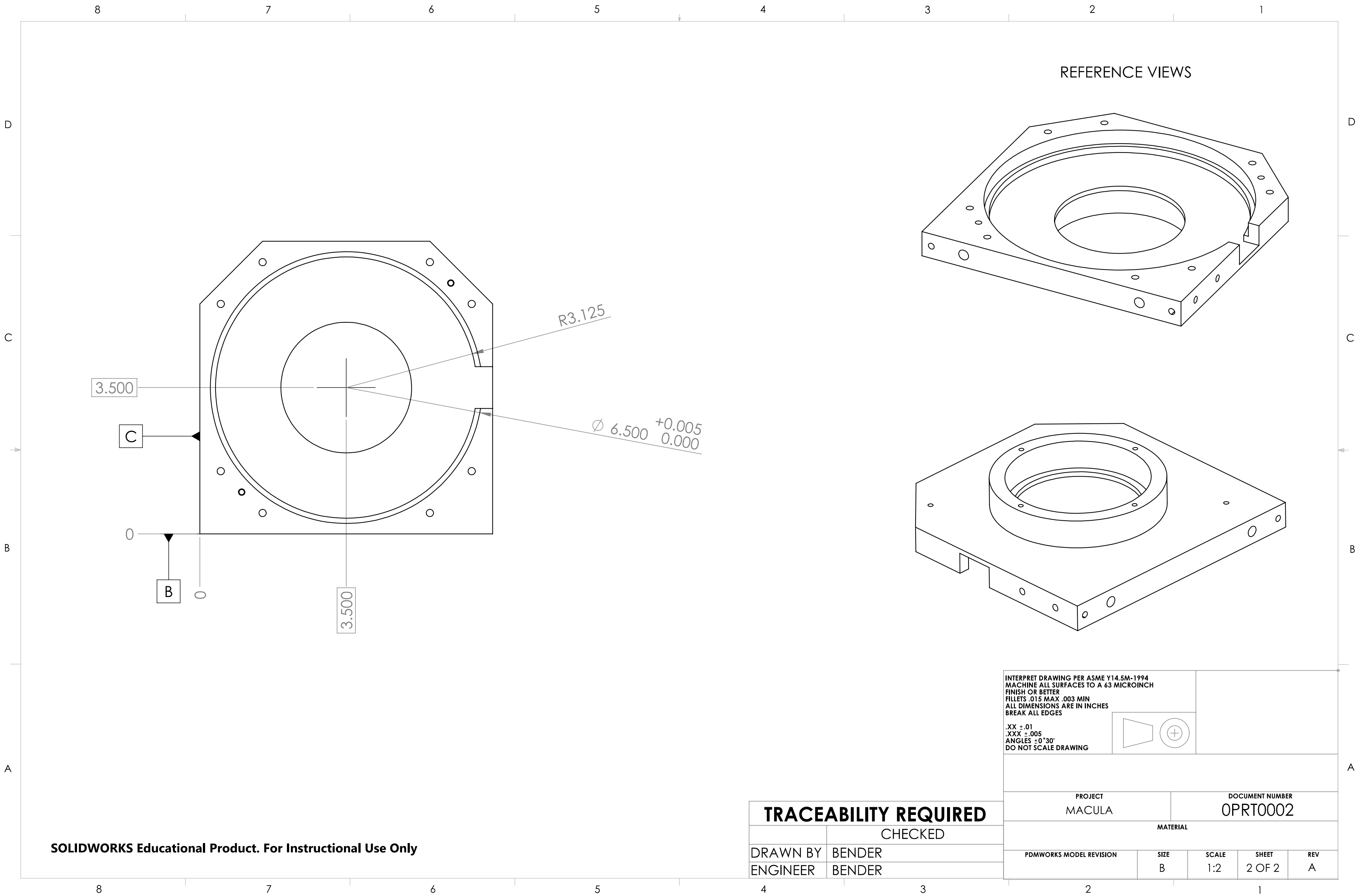
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES

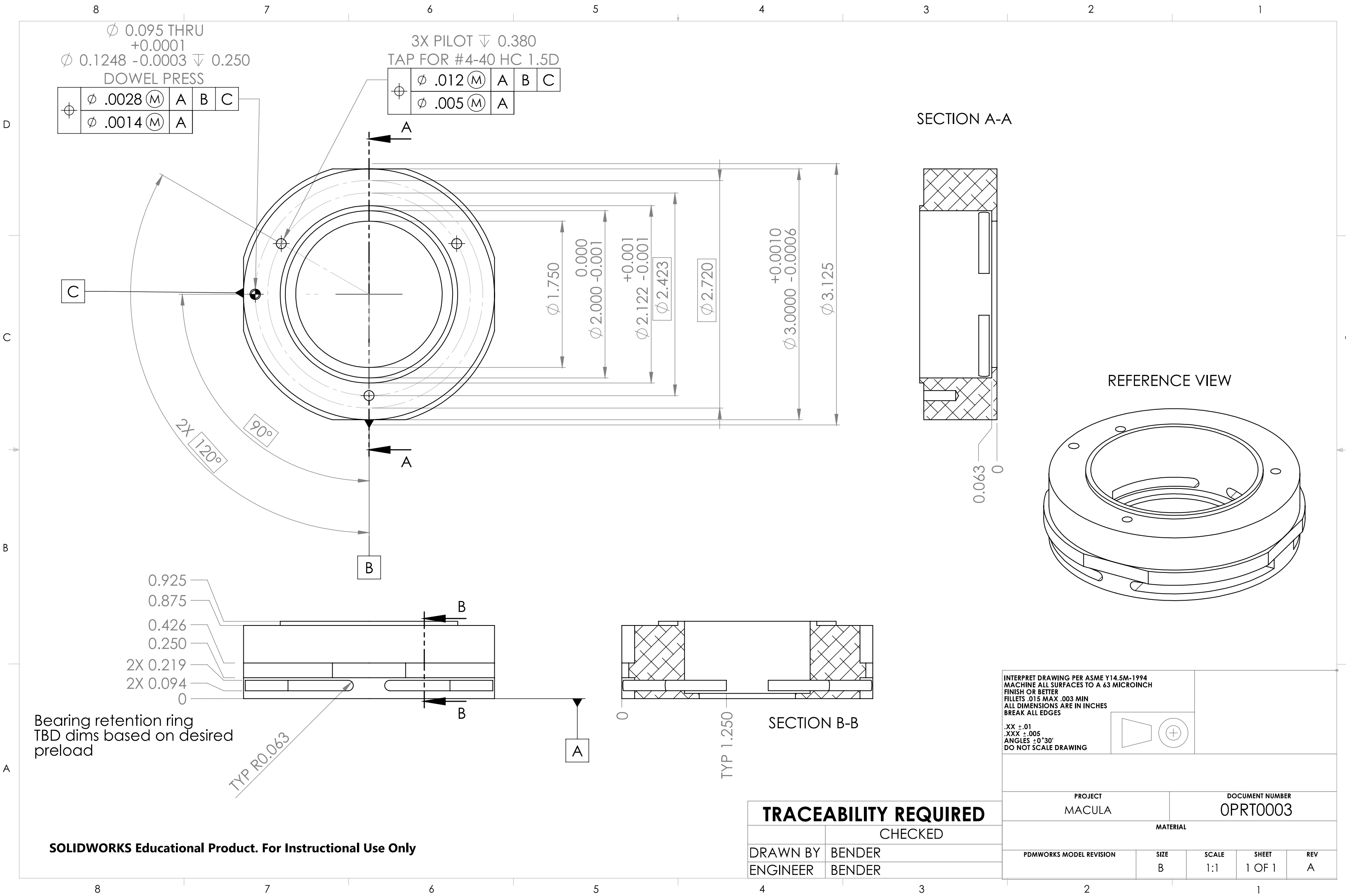
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING

PROJECT	DOCUMENT NUMBER
MACULA	0PRT0002

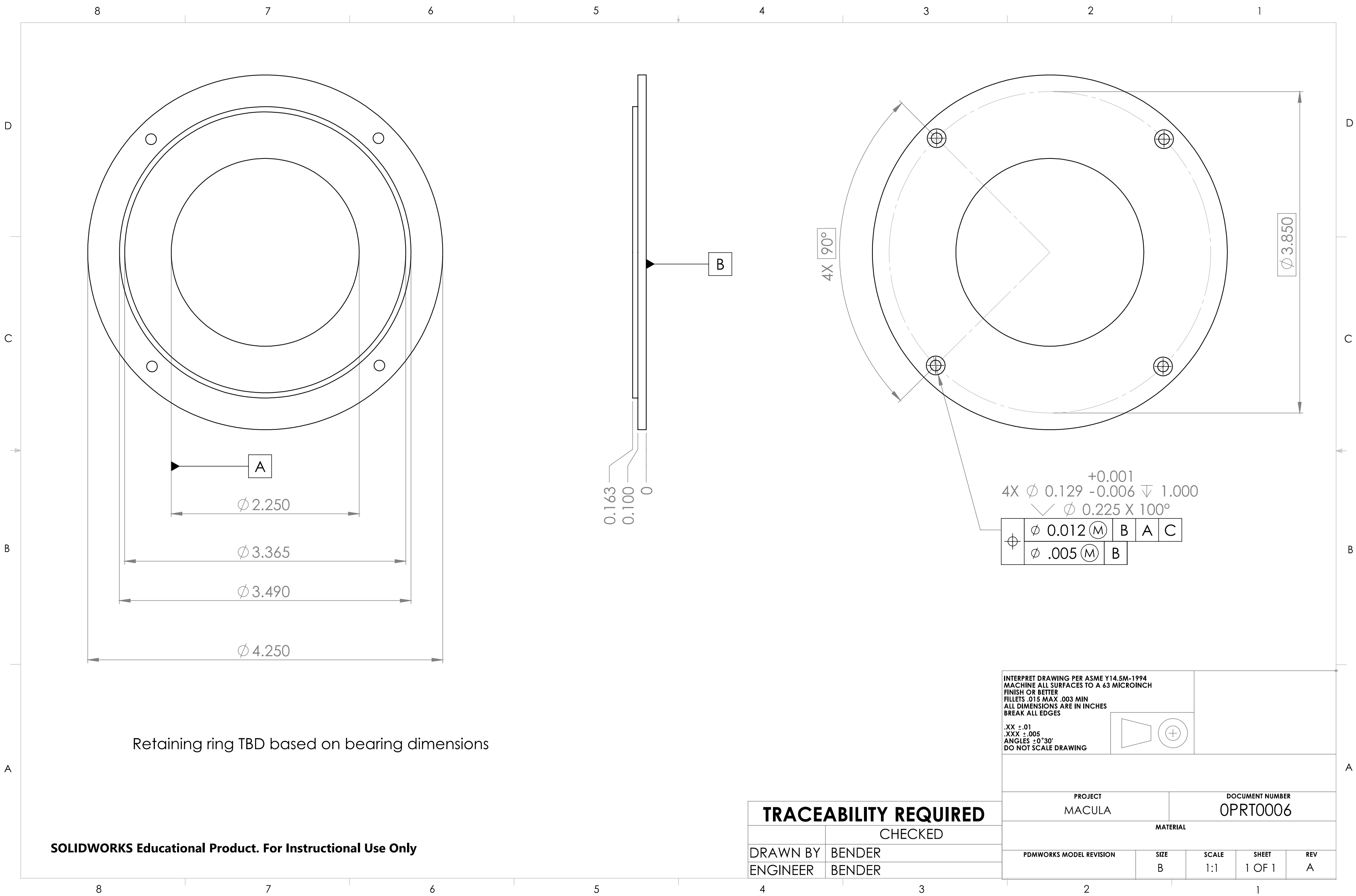
MATERIAL

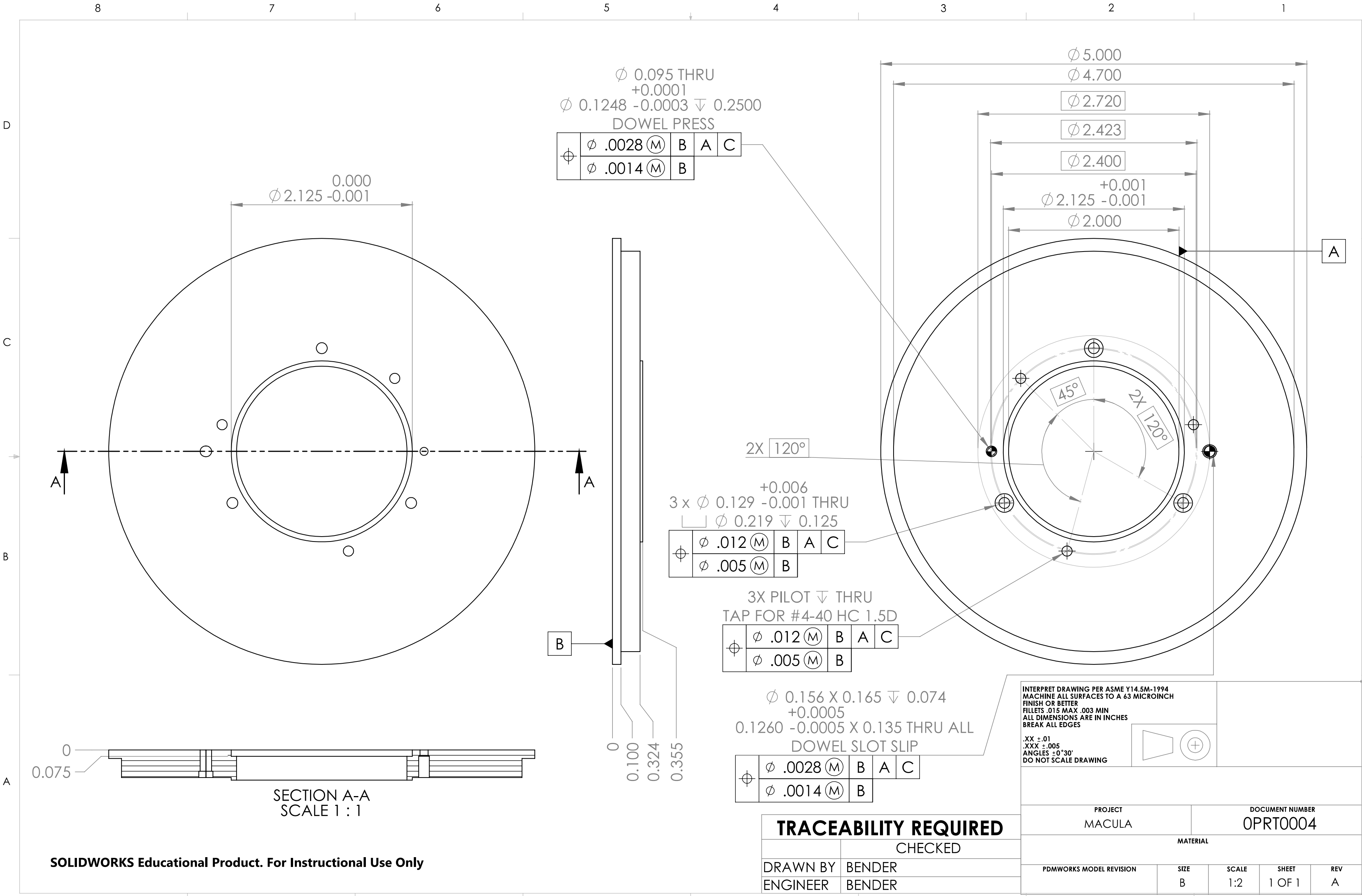
PDMWORKS MODEL REVISION	SIZE	SCALE	SHEET	REV
	B	1:2	1 OF 2	A


REFERENCE VIEWS
R3.125
3.500
C
∅ 6.500 +0.005 0.000
0
B
0
3.500
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH
FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT
MACULA
DOCUMENT NUMBER
0PRT0002
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:2
SHEET 2 OF 2
REV A
SOLIDWORKS Educational Product. For Instructional Use Only

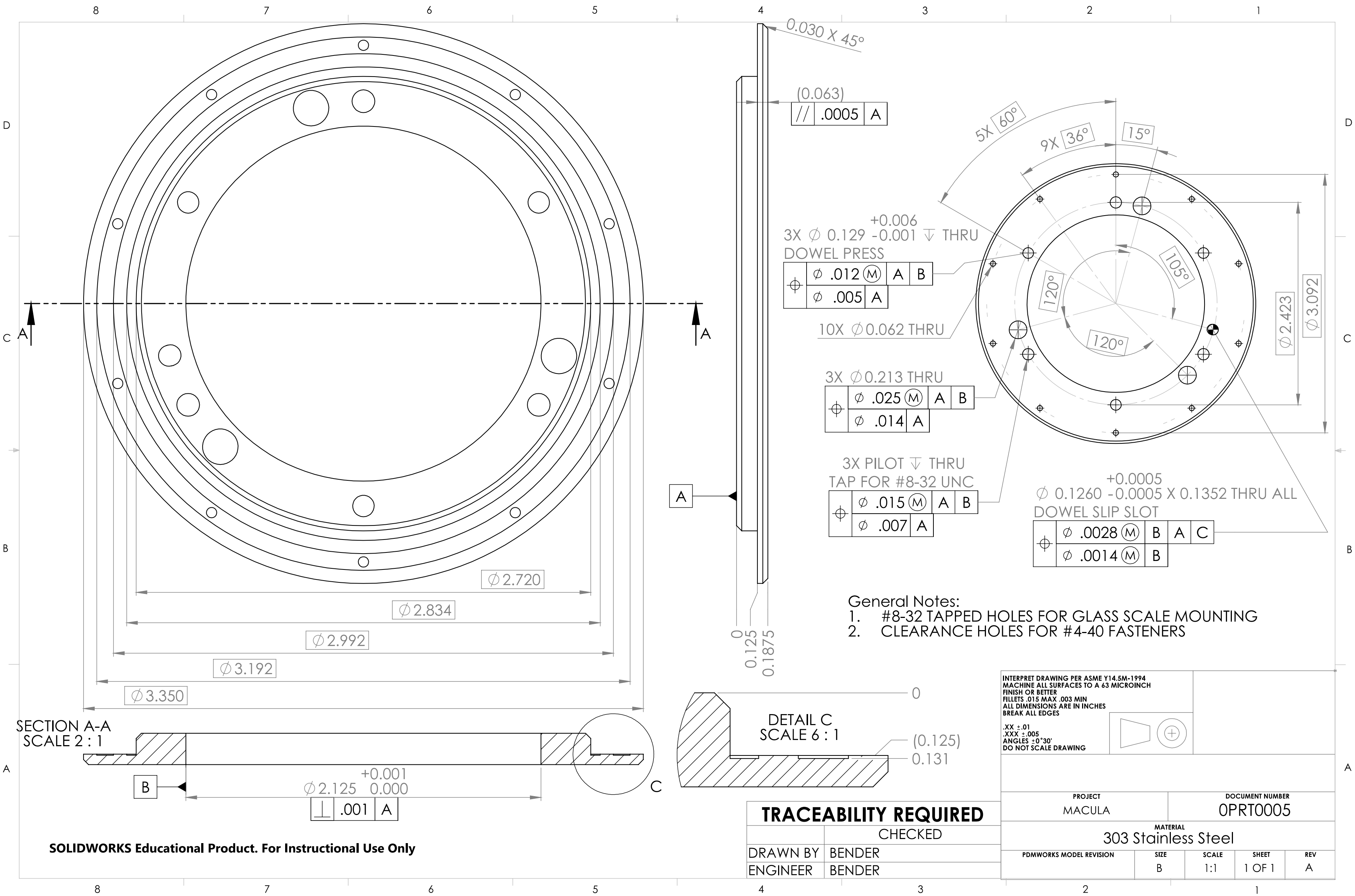


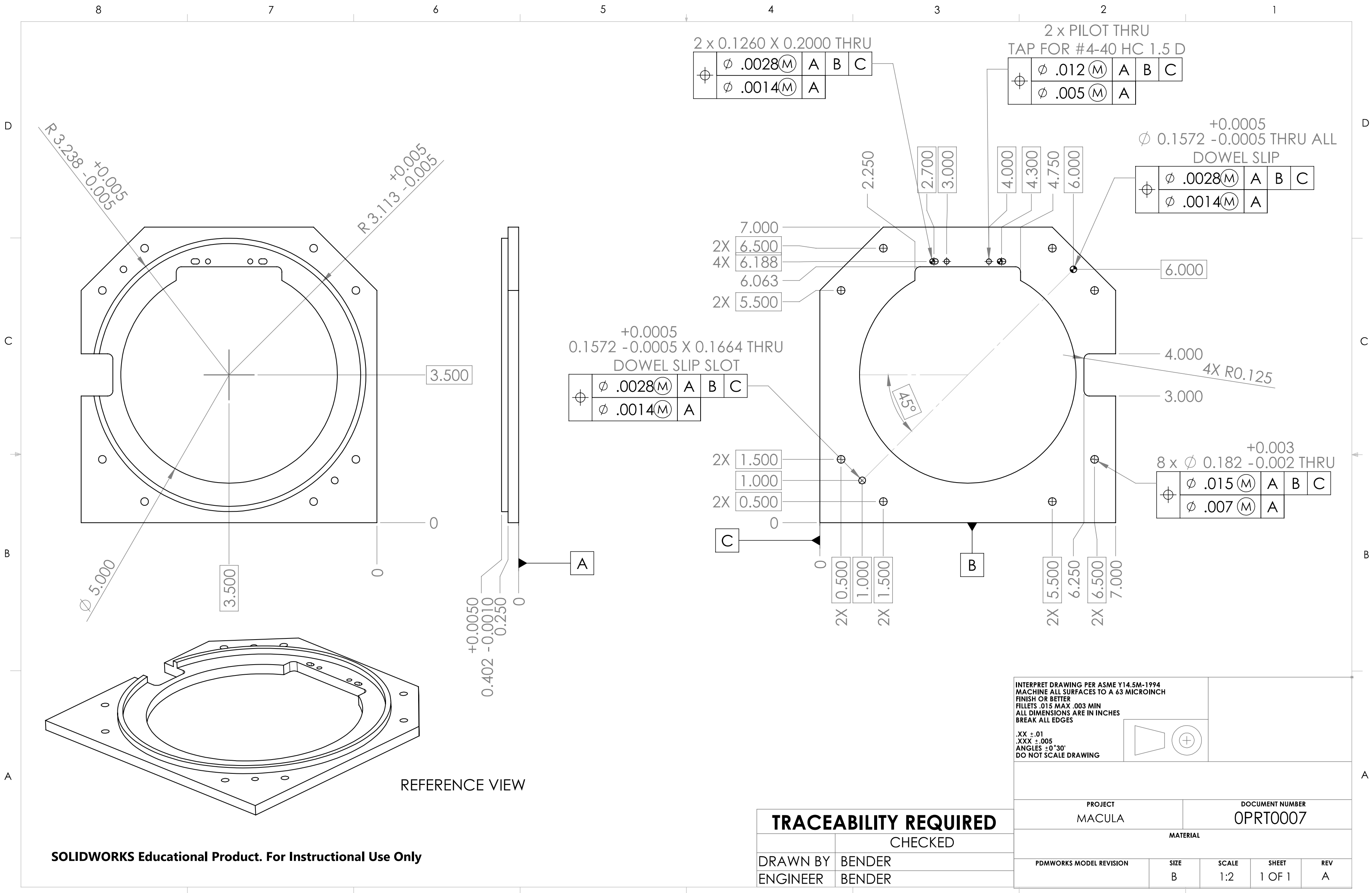
∅ 0.095 THRU
∅ 0.1248 +0.0001 -0.0003 ↧ 0.250
DOWEL PRESS
⌖ ∅ .0028 Ⓜ A B C
∅ .0014 Ⓜ A
3X PILOT ↧ 0.380
TAP FOR #4-40 HC 1.5D
⌖ ∅ .012 Ⓜ A B C
∅ .005 Ⓜ A
SECTION A-A
A
C
∅ 1.750
∅ 2.000 0.000 -0.001
∅ 2.122 +0.001 -0.001
∅ 2.423
∅ 2.720
∅ 3.0000 +0.0010 -0.0006
∅ 3.125
90°
2X 120°
B
0.063
0
REFERENCE VIEW
0.925
0.875
0.426
0.250
2X 0.219
2X 0.094
0
Bearing retention ring
TBD dims based on desired preload
TYP R0.063
TYP 1.250
SECTION B-B
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0003
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:1
SHEET 1 OF 1
REV A
SOLIDWORKS Educational Product. For Instructional Use Only


A
B
⌀2.250
⌀3.365
⌀3.490
⌀4.250
0.163
0.100
0
4X 90°
⌀3.850
4X ⌀ 0.129 +0.001 -0.006 ↧ 1.000
⌵ ⌀ 0.225 X 100°
⌀ 0.012 Ⓜ B A C
⌀ .005 Ⓜ B
Retaining ring TBD based on bearing dimensions
SOLIDWORKS Educational Product. For Instructional Use Only
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0006
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:1
SHEET 1 OF 1
REV A



∅ 0.095 THRU
+0.0001
∅ 0.1248 -0.0003 ↧ 0.2500
DOWEL PRESS
0.000
∅2.125 -0.001
∅5.000
∅4.700
∅2.720
∅2.423
∅2.400
+0.001
∅2.125 -0.001
∅2.000
45°
2X 120°
2X 120°
+0.006
3 x ∅ 0.129 -0.001 THRU
⌴ ∅ 0.219 ↧ 0.125
3X PILOT ↧ THRU
TAP FOR #4-40 HC 1.5D
∅ 0.156 X 0.165 ↧ 0.074
+0.0005
0.1260 -0.0005 X 0.135 THRU ALL
DOWEL SLOT SLIP
SECTION A-A
SCALE 1 : 1
0
0.075
0
0.100
0.324
0.355
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0004
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:2
SHEET 1 OF 1
REV A
SOLIDWORKS Educational Product. For Instructional Use Only


0.030 X 45°
(0.063)
// .0005 A
5X 60°
9X 36°
15°
+0.006
3X ∅ 0.129 -0.001 ↧ THRU
DOWEL PRESS
∅ .012 Ⓜ A B
∅ .005 A
105°
120°
120°
∅2.423
∅3.092
10X ∅0.062 THRU
3X ∅0.213 THRU
∅ .025 Ⓜ A B
∅ .014 A
3X PILOT ↧ THRU
TAP FOR #8-32 UNC
∅ .015 Ⓜ A B
∅ .007 A
+0.0005
∅ 0.1260 -0.0005 X 0.1352 THRU ALL
DOWEL SLIP SLOT
∅ .0028 Ⓜ B A C
∅ .0014 Ⓜ B
A
∅2.720
∅2.834
∅2.992
∅3.192
∅3.350
0
0.125
0.1875
General Notes:
1. #8-32 TAPPED HOLES FOR GLASS SCALE MOUNTING
2. CLEARANCE HOLES FOR #4-40 FASTENERS
SECTION A-A
SCALE 2 : 1
B
+0.001
∅2.125 0.000
⊥ .001 A
C
DETAIL C
SCALE 6 : 1
0
(0.125)
0.131
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0005
MATERIAL 303 Stainless Steel
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:1
SHEET 1 OF 1
REV A
SOLIDWORKS Educational Product. For Instructional Use Only

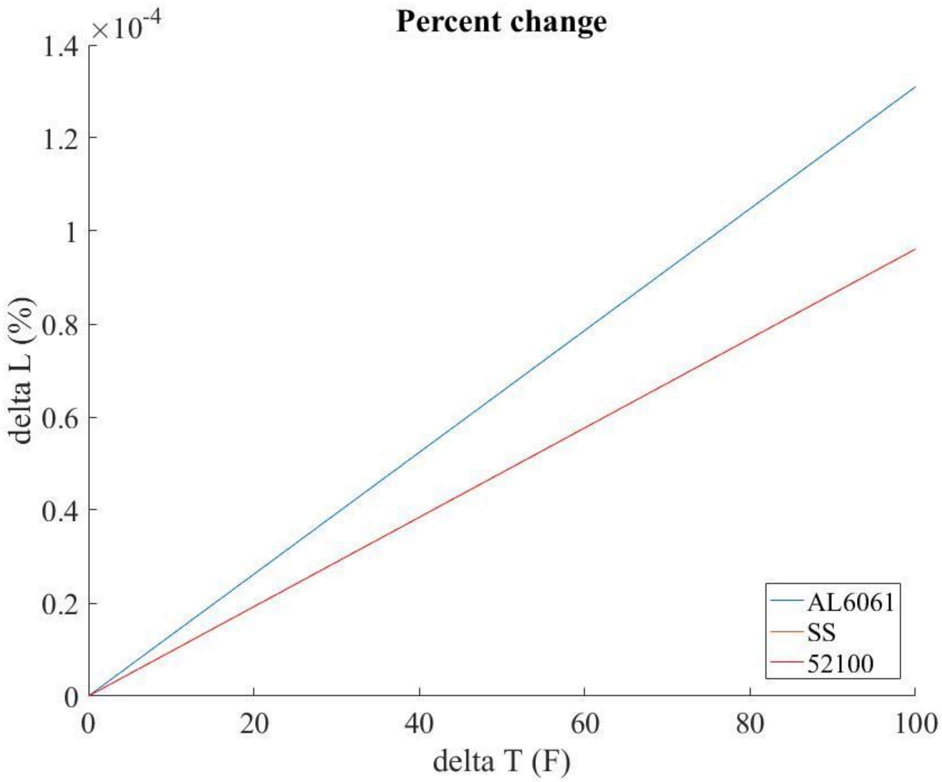


2 x 0.1260 X 0.2000 THRU
⌖ ∅ .0028Ⓜ A B C
∅ .0014Ⓜ A
2 x PILOT THRU
TAP FOR #4-40 HC 1.5 D
⌖ ∅ .012Ⓜ A B C
∅ .005Ⓜ A
+0.0005
∅ 0.1572 -0.0005 THRU ALL
DOWEL SLIP
⌖ ∅ .0028Ⓜ A B C
∅ .0014Ⓜ A
R 3.238 +0.005 -0.005
R 3.113 +0.005 -0.005
3.500
0
∅ 5.000
3.500
0
+0.0050
0.402 -0.0010
0.250
0
A
+0.0005
0.1572 -0.0005 X 0.1664 THRU
DOWEL SLIP SLOT
⌖ ∅ .0028Ⓜ A B C
∅ .0014Ⓜ A
2.250
2.700
3.000
4.000
4.300
4.750
6.000
7.000
2X 6.500
4X 6.188
6.063
2X 5.500
6.000
4.000
4X R0.125
3.000
45°
2X 1.500
1.000
2X 0.500
0
C
B
+0.003
8 x ∅ 0.182 -0.002 THRU
⌖ ∅ .015Ⓜ A B C
∅ .007Ⓜ A
0
2X 0.500
1.000
2X 1.500
2X 5.500
6.250
2X 6.500
7.000
REFERENCE VIEW
SOLIDWORKS Educational Product. For Instructional Use Only
INTERPRET DRAWING PER ASME Y14.5M-1994
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER
FILLETS .015 MAX .003 MIN
ALL DIMENSIONS ARE IN INCHES
BREAK ALL EDGES
.XX ±.01
.XXX ±.005
ANGLES ±0°30'
DO NOT SCALE DRAWING
TRACEABILITY REQUIRED
CHECKED
DRAWN BY BENDER
ENGINEER BENDER
PROJECT MACULA
DOCUMENT NUMBER 0PRT0007
MATERIAL
PDMWORKS MODEL REVISION
SIZE B
SCALE 1:2
SHEET 1 OF 1
REV A

BACKUP: MATERIAL ANALYSIS

Thermal

- Linear Thermal Expansion: $\Delta l = l_0 \alpha (T_f - T_o)$



<u>Thermal Expansion Coefficients</u>

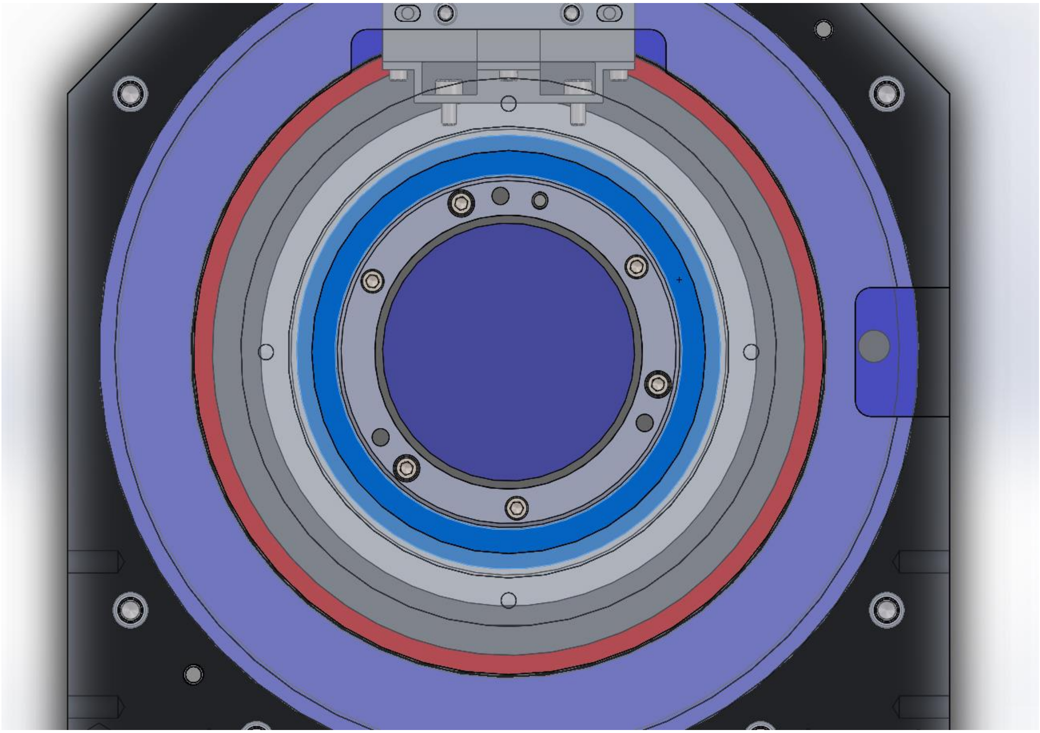
- $\alpha_{al} = 13.1 \frac{\mu in}{inF}$
- $\alpha_{ss} = 6.61 \frac{\mu in}{inF}$
- $\alpha_{52100} = 9.61 \frac{\mu in}{inF}$

<u>Max error (5°F)</u>

- 0.003806°
- 2.5% of error budget

Mechanical

- Steel dowel pin
  - $V_{max} =$ 7117 N
  - $\tau_{allow} =$ 246 Nm
  - $\tau_{max} =$ 1.26 Nm
  - FOS = 202



BACKUP: RISKS

Mitigation

R2	Encoder mount damage occurs during shipping, glass scale installation, or storage
	1. Ensure safe packing of encoder hubs when shipped out to company
	Reduces likelihood of risk
	2. Manufacture additional encoder hub and buy additional glass scale
	Stock materials can be bought with 20% budget margin
	Reduces severity of risk

Type of Risk

- ☐ Budget
- ☑ Technical
- ☐ Safety
- ☑ Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3					
	2			2	X	
	1			1/2	1	

Mitigation

R3	Limited machine shop availability due to schedules and use by other students
	1. Go over manufacturing plans ahead of time to ensure efficient use of time in shop
	Reduces likelihood of risk
	2. Utilize full extent of machining resources available, included multiple shops (Aero, ITLL) and full time employees who will machine parts
	Reduces severity of risk

Type of Risk

- ☐ Budget
- ☐ Technical
- ☐ Safety
- ☑ Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4	2	X			
	3	1/2	1			
	2					
	1					

Mitigation

R4	Risley prism damage occurs during storage or handling
	1. Ensure proper padding / protection is in place when storing and moving prisms
	Reduces likelihood of risk
	2. Limit contact with prisms before and during mounting in system
	Reduces likelihood of risk

Type of Risk

- ☑ Budget
- ☑ Technical
- ☐ Safety
- ☐ Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3					
	2				X	
	1				1/2	

Mitigation

R5	RECUV test facility unavailable at necessary times and/or necessary durations
	1. Coordinate testing times far in advance to ensure availability
	Reduces likelihood of risk
	2. Run through test procedures before testing on location for efficient use of time
	Reduces likelihood of risk

Type of Risk

- ☐ Budget
- ☐ Technical
- ☐ Safety
- ☑ Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3					
	2			X		
	1			1/2		

BACKUP: HARDWARE TRADE STUDIES

Position Sensor Trade Study

Metric	1	2	3	4	5
Resolution	$\geq 0.15°$	$\geq 0.075°$	$\geq 0.0375°$	$\geq 0.0187°$	$\geq 0.0094°$
Interface/Decoding	Not a common on chip peripheral	-	-	-	Common on chip peripheral
Cost per	$\geq$ $600	$\geq$ $500	$\geq$ $400	$\geq$ $300	$\geq$ $200

	Weight	Absolute	Incremental	Sin Cos In-cremental	Rotary Poten-tiometer	Resolver
Resolution	50%	3	4	5	1	3
Interface	40%	1	5	1	5	1
Cost	10%	2	2	2	5	1
Sum	100%	2.1	**4.2**	3.1	3.0	2.0

Encoder Trade Study

Metric	1	2	3	4	5
Cost	≥ \$1400	≥ \$1200	≥ \$1000	≥ \$800	≥ \$600
Immunity to Environment	Knocked out by a slight breeze	Constant Interference	Innately exposed scanning head	Innately shrouded scanning head	Impervious
Design Flexibility	Any change requires replacing both scanning head and scale	Diameter change requires replacing both scanning head and scale	Scale change requires replacing both scanning head and scale	-	Scanning head and scale may be changed in-dependently of each other, diameter only affects scale

	Weight	OPS Series	IncOder Series	Lika SMR Series	Heidenhain
Cost	40%	5	3	5	1
Immunity to Environment	30%	3	5	2	4
Design Flexibility	30%	5	2	5	5
Sum	100%	**4.4**	3.3	4.1	3.1

Motor Driver Trade Study

Metric	1	2	3	4	5
Cost	$\geq$ \$500	$\geq$ \$400	$\geq$ \$300	$\geq$ \$200	$\geq$ \$100
Development Time	Build board, create control law, tuning	-	Create control law, then tune	-	Just tuning
Modes of control	Torque / Current	-	Velocity, Torque / Current	-	Position, Velocity, Torque / Current
Commutation / Feedback	Hall effect	-	Sensor-less	-	Encoder Feedback

	Weight	Custom	AMC Servo Drivers	TI BLDC Motor Controllers	ST Eval Boards
Cost	10%	5	2	5	5
Development Time	40%	1	5	3	3
Modes of control	20%	5	5	3	5
Commutation / Feedback	30%	5	5	3	5
Sum	100%	3.4	**4.7**	3.2	4.2

Microcontroller Trade Study

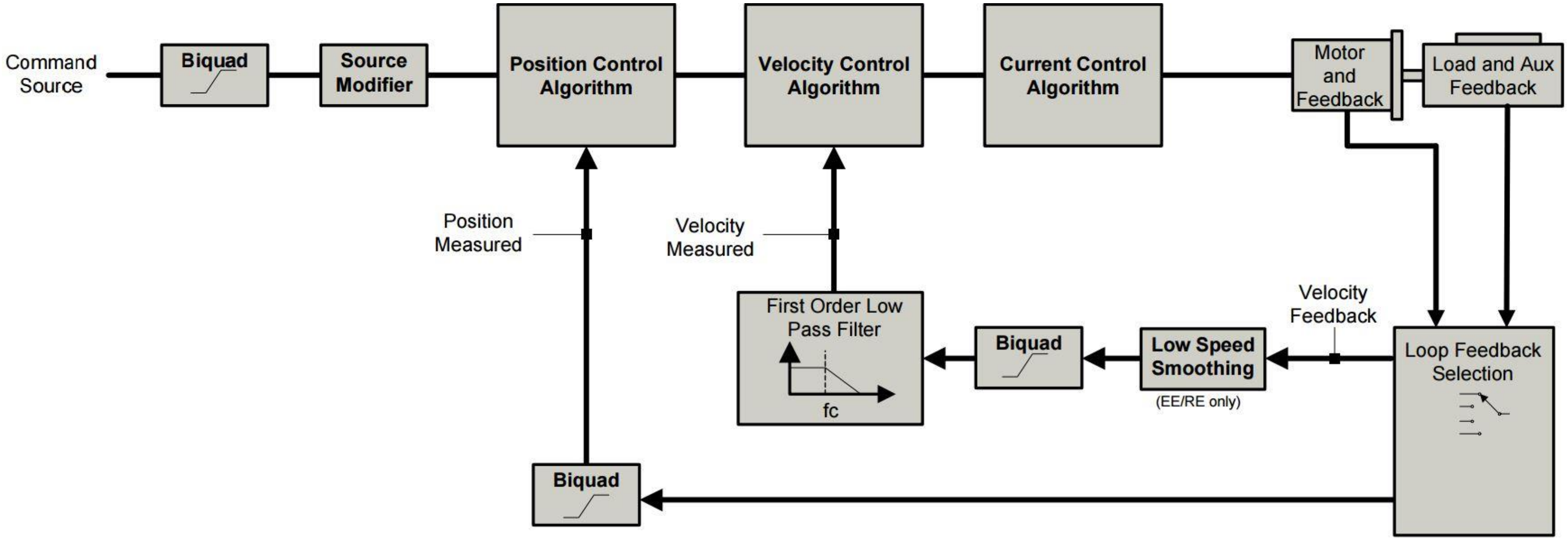
Metric	1	2	3	4	5
Cost	$\geq$ \$500	$\geq$ \$400	$\geq$ \$300	$\geq$ \$200	$\geq$ \$100
Development Time	Build board from scratch	-	Bare Metal C	Has an OS or a third party application to ease development	OS, can use previously written Python scripts
Peripherals	Does not have any needed	Has only ADC	Has ADC, and UART	Has ADC, UART, USB/Ethernet	Has ADC, UART, USB/Ethernet, quadrature decoders
Design Flexibility	Component changes requires a different mi-crocontroller	-	Component changes requires additional chips to handle them, but can interface with microcon-troller	Program FPGA to adapt	Easy to adjust to component changes

	Weight	Custom	BeagleBone Black	Pi Series	MyRio	ZedBoard
Cost	15%	4	5	5	1	3
Development Time	30%	1	5	5	4	5
Peripherals	40%	5	5	3	5	5
Design Flexibility	15%	5	3	3	4	3
Sum	100%	3.65	**4.7**	3.9	3.95	4.4

BACKUP: MOTOR/PRISM CONTROL

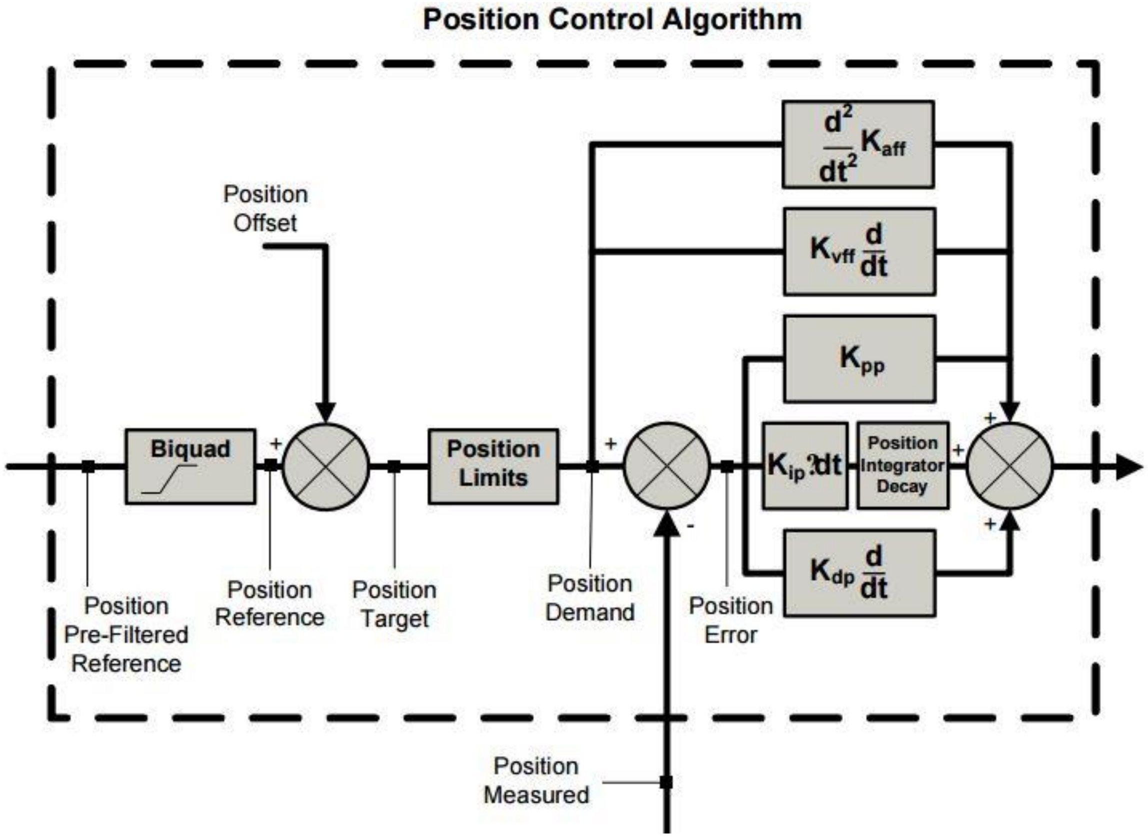
Control Loop

- Built in feedback control
- Primary positional or velocity control



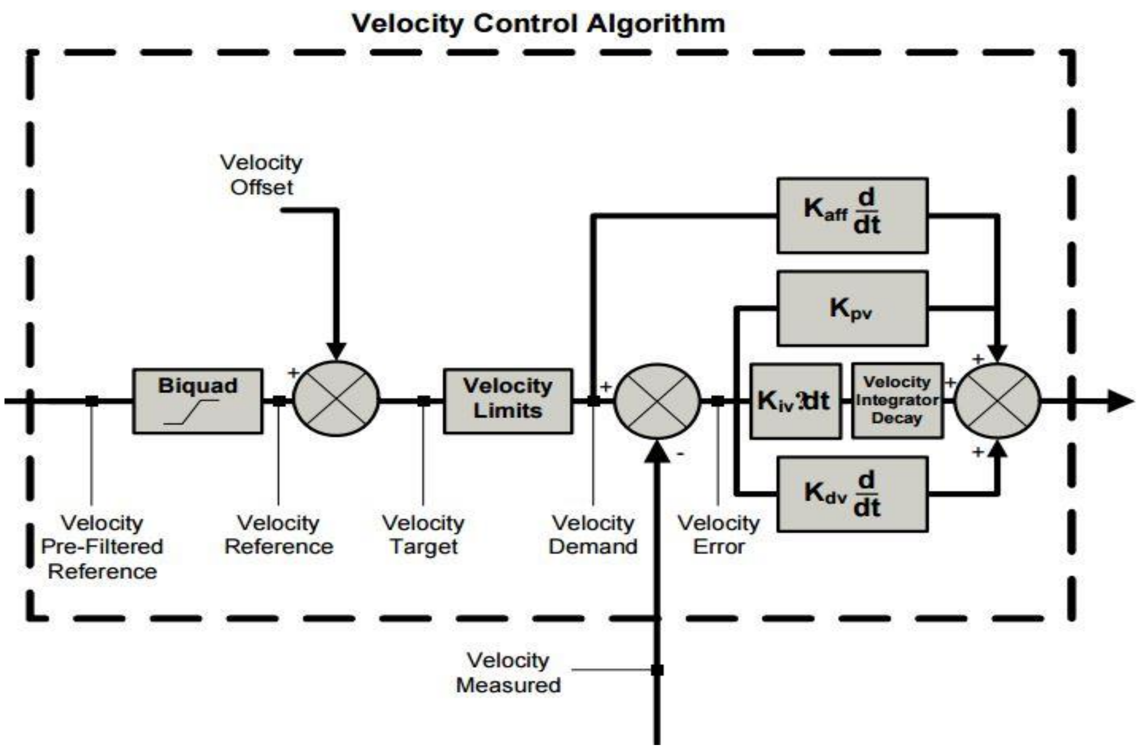
Position Control

- P.I.D control
- Feedforward acceleration and velocity



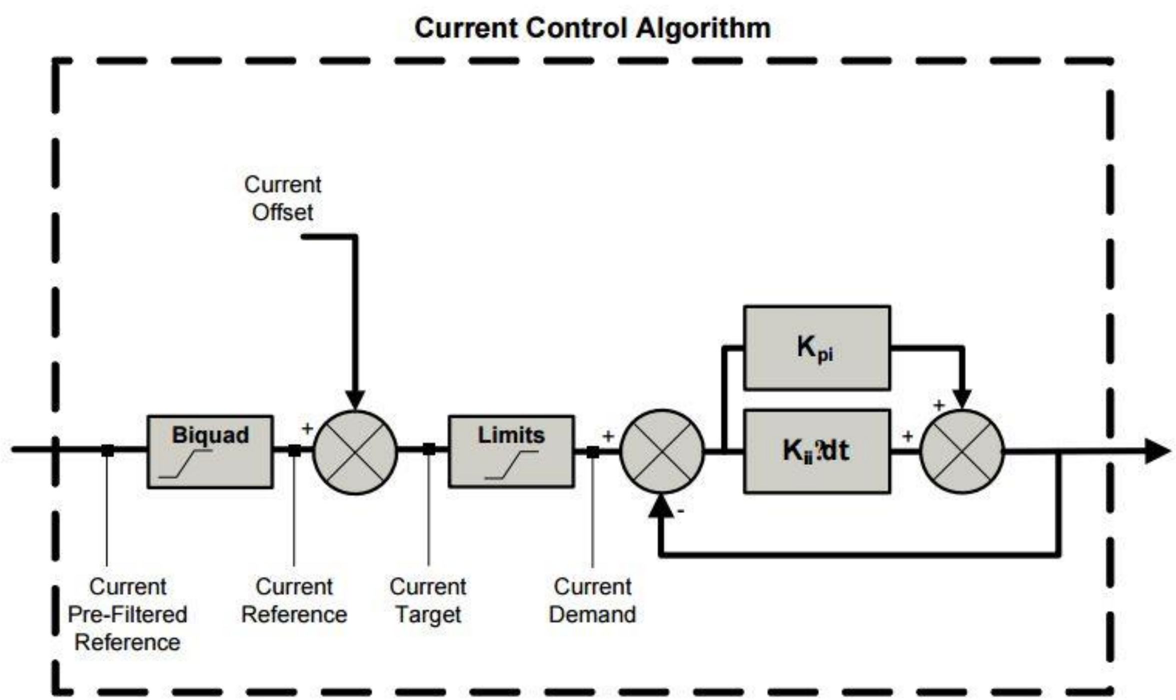
Position around Velocity

- Used when position trajectory must be tracked closely
- Feed forward gains added for better tracking



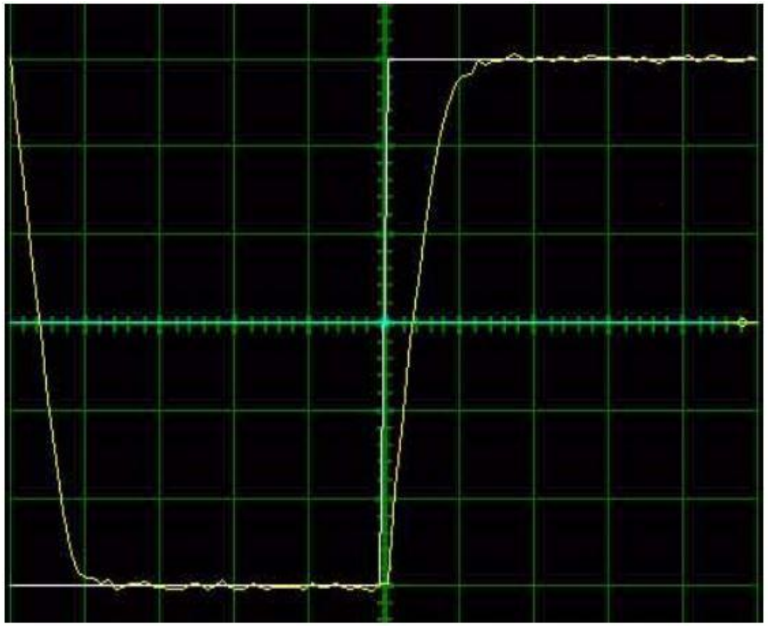
Position around Torque

- Point-to-point applications



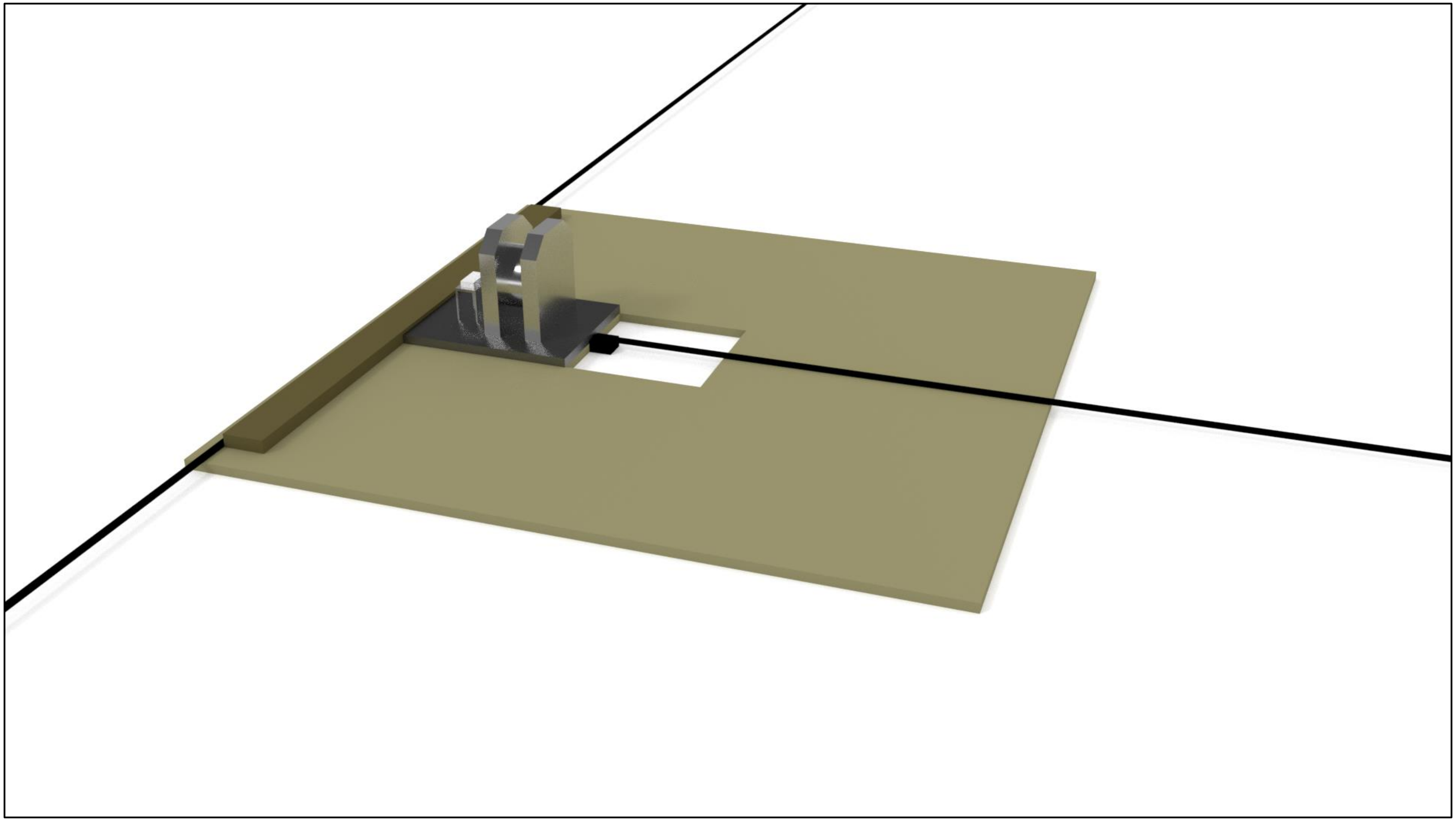
Tuning

- Performed with a motor installed into system
- Oscilloscope
  - 1-3Hz square wave
  - Channel one: Position Target
  - Channel two: Position Measured
- Gains initialized to zero
  - $0 \leq Kp \leq 0.5$
  - $0 \leq Ki \leq 9.766$
  - $0 \leq Kd \leq 0.0008$
  - $0 \leq Kv \leq 0.0008$
  - $0 \leq Ka \leq 8$ x



BACKUP: CALIBRATION

Test Plan: Calibration (Close-up)



Theodolite

What does it do?

- Determines vertical and horizontal angles of surveyed

How does it work?

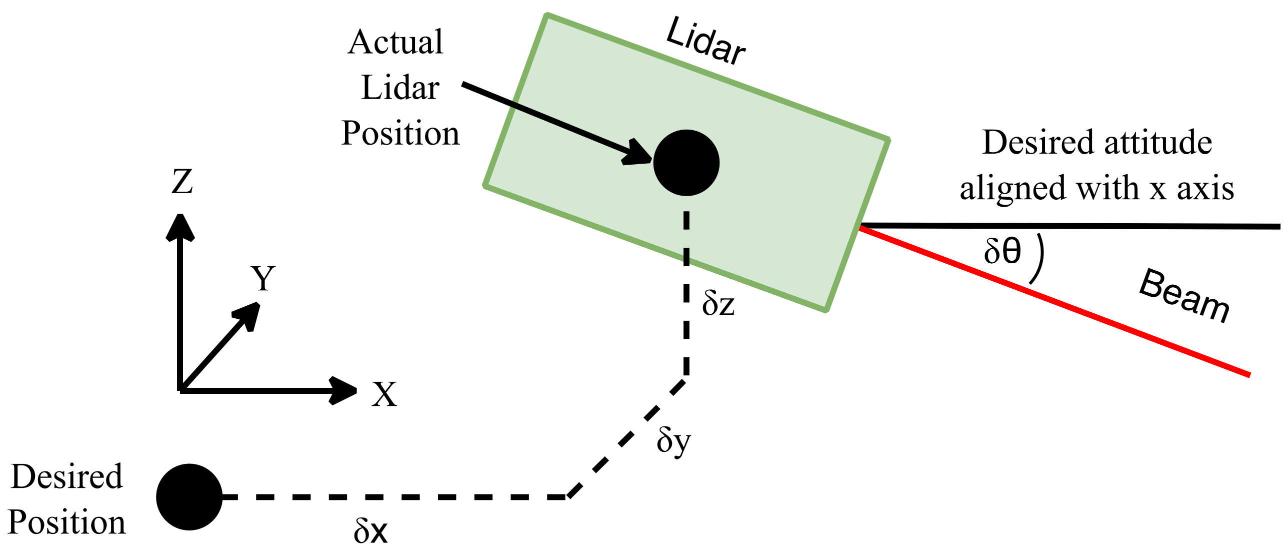
- Plumb bobs ensures that it is vertical relative to the surveying point
- Internal bubble level ensures that it is level relative to the horizon
- Graduated circles allow for horizontal and vertical angles of surveyed object to be measured

Sources of Error

Must be Calibrated
System Inherent

Lidar:

- Translational deviations
- Rotational deviations
- Beam divergence

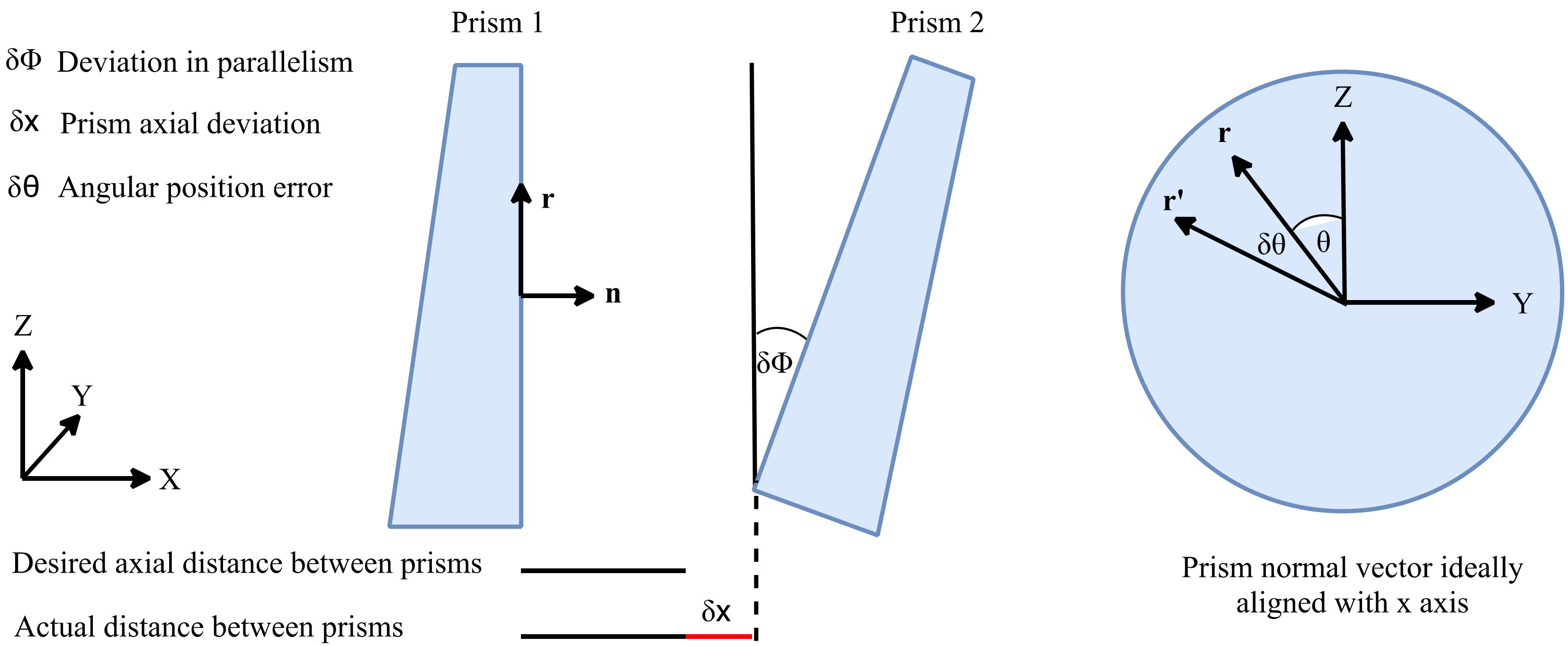


Sources of Error

Prisms:

- Uncertainty in wedge angle
- Uncertainty in index of refraction

Acceptable / Easily Mitigated
Must be Calibrated

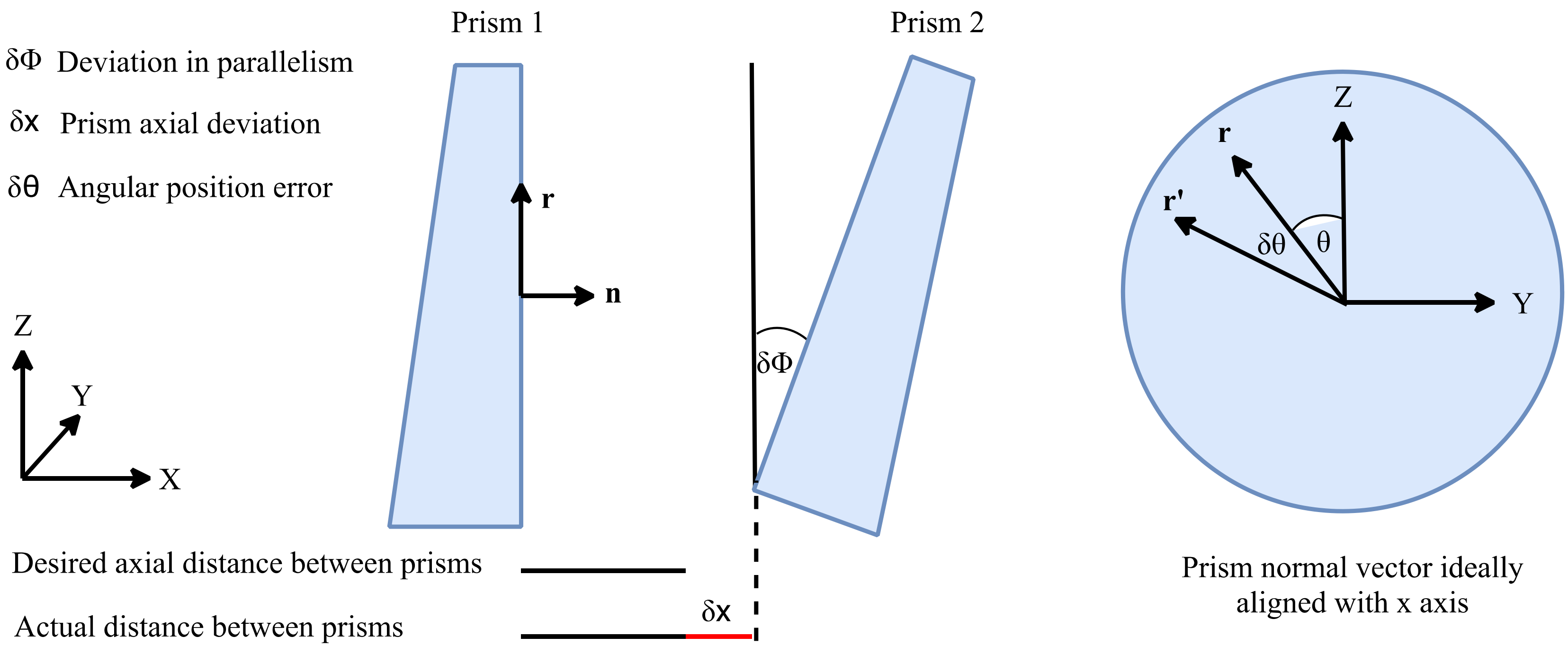


Sources of Error

Prisms:

- Uncertainty in angular position
- Deviation from parallelism
- Translational deviations

Acceptable / Easily Mitigated
Must be Calibrated

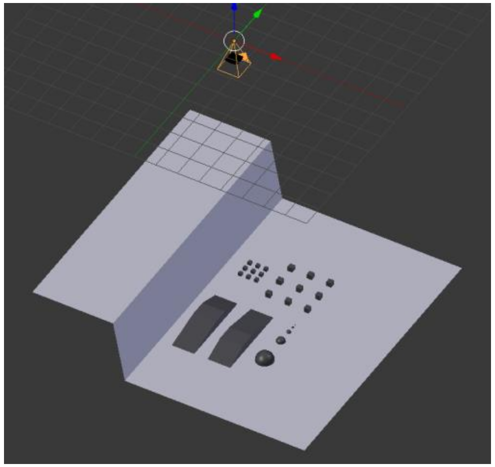


BACKUP: SOFTWARE/ALGORITHM

Blender Lidar Simulator

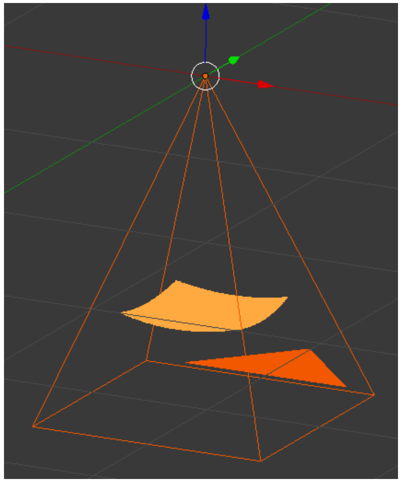
- Blender is an open-source program for 3D modeling
- Projects points onto any arbitrary face or object to simulate a lidar scan
- Can extract 3D data by running Python scripts within Blender

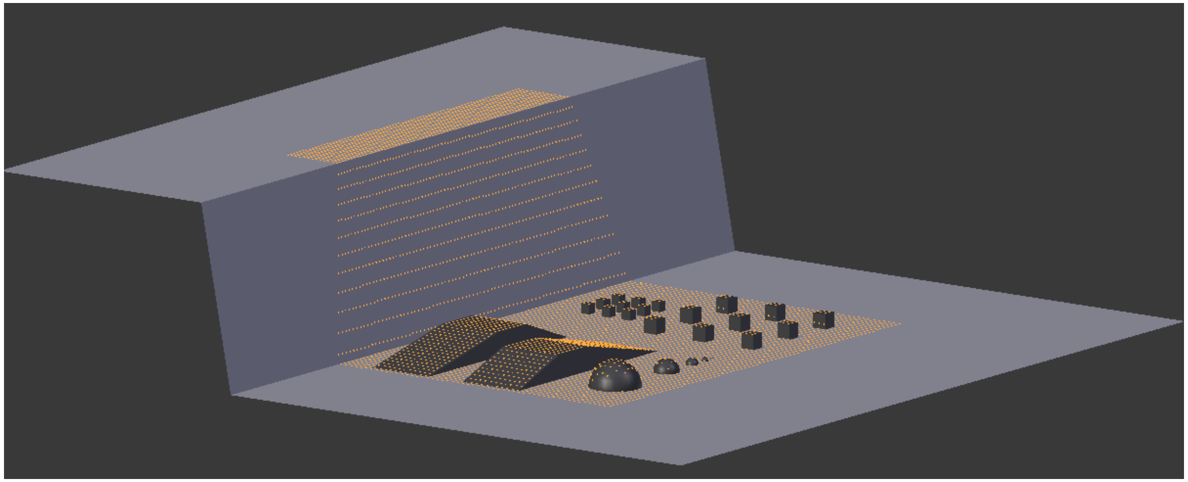
Example Blender artwork



Blender Lidar Simulator

- Scan pattern is defined on the plane of the ground, and projected backward onto a sphere centered on the lidar (Blender camera)
- The pattern is then projected outward from the lidar location onto the modeled map
- A Python script exports the point cloud to a CSV file

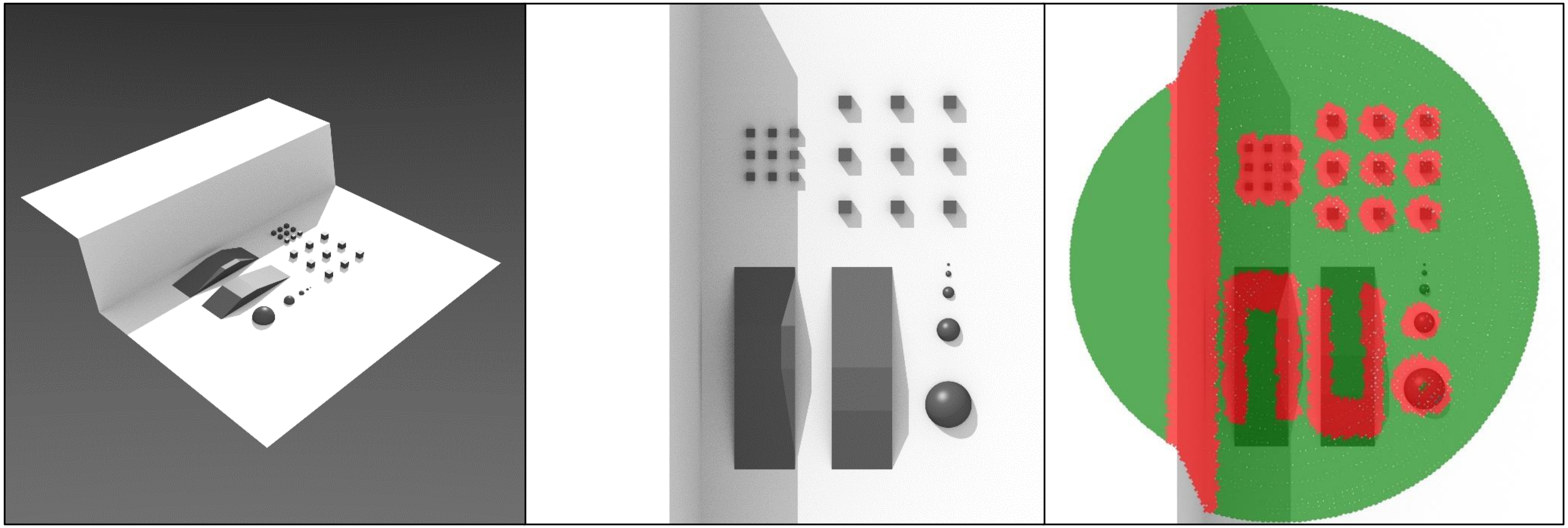




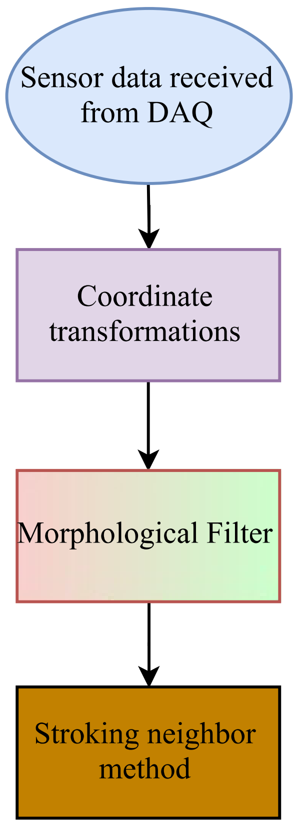
Hazard Detection Algorithms

Morphological Filter

- Identifies hazards by height differences between neighboring points
- Time to run on laptop: 0.31 sec for 10 cm grid



Time Estimates



Estimated time: 0.33 s

Estimated time: 0.31 s

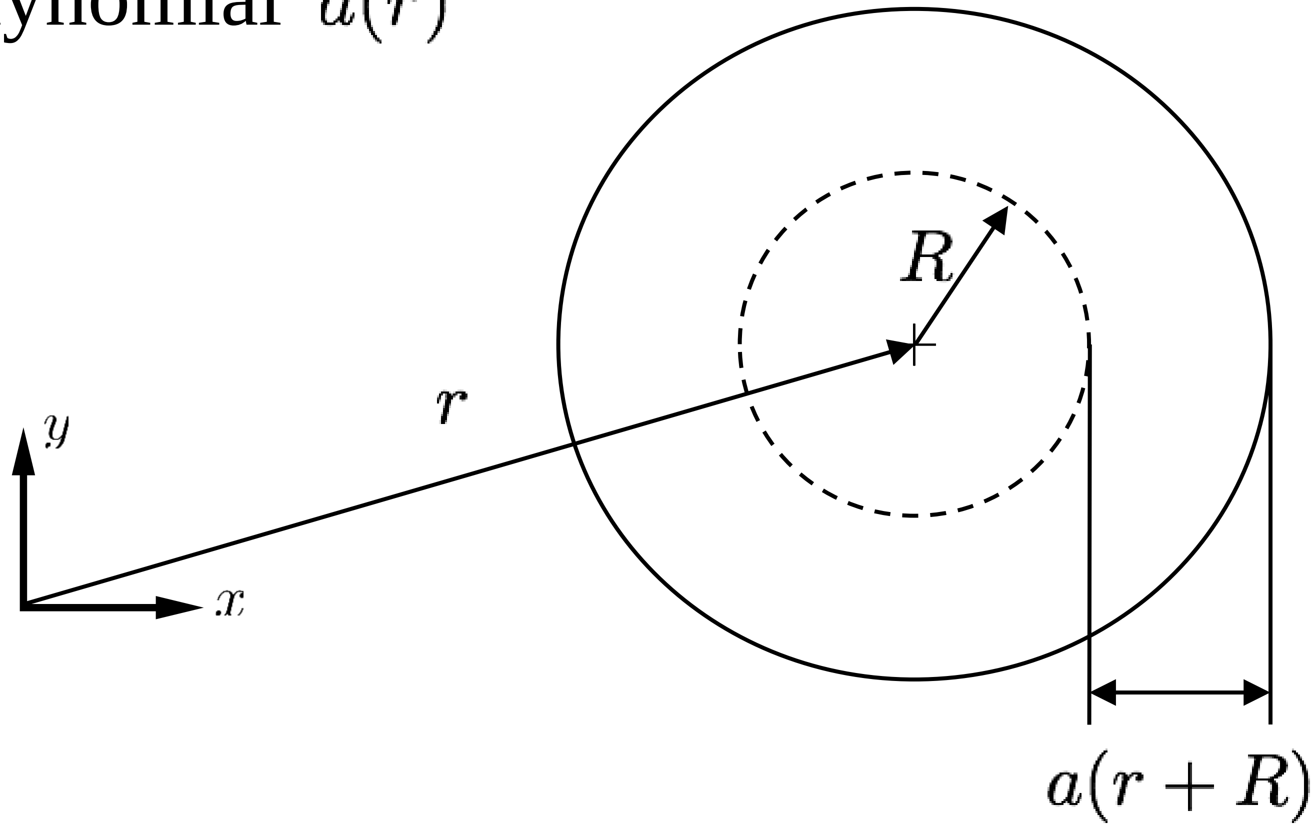
Estimated time: 0.026 s

Estimated total time for software elements when run in Python on a personal laptop: about **0.666 s**

Analysis shows that the BeagleBone will run ~10.24 times slower (**6.83 s**). Given our 10 s margin, we will be well within the time requirement even after porting to the microprocessor. More computationally expensive functions may be written in C for speed improvements.

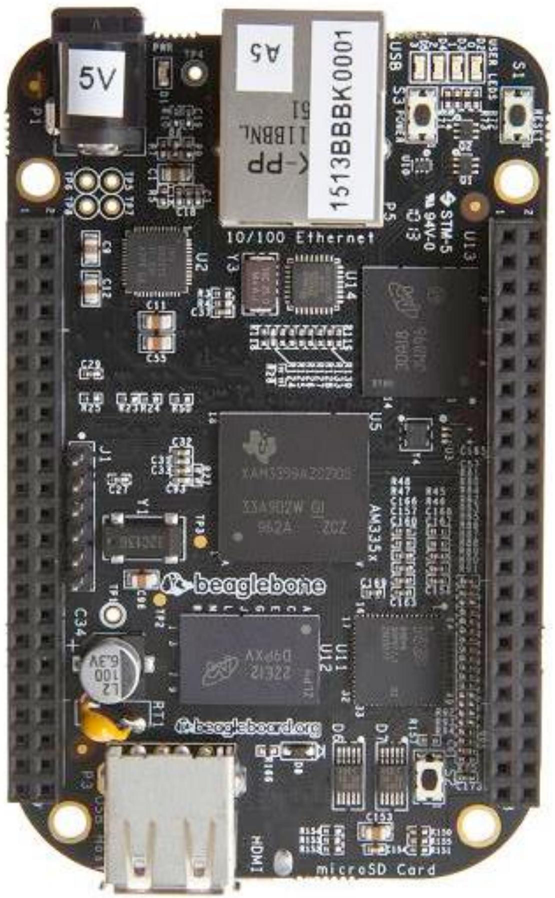
Error Compensation

We fit the semimajor axis of the error ellipse to a polynomial $a(r)$



BACKUP: BEAGLEBONE

BeagleBone Black Rev C.1



	Feature	
Processor	Sitara AM3358BZCZ100 1GHz, 2000 MIPS	
Graphics Engine	SGX530 3D, 20M Polygons/S	
SDRAM Memory	512MB DDR3L 800MHZ	
Onboard Flash	4GB, 8bit Embedded MMC	
PMIC	TPS65217C PMIC regulator and one additional LDO.	
Debug Support	Optional Onboard 20-pin CTI JTAG, Serial Header	
Power Source	miniUSB USB or DC Jack	5VDC External Via Expansion Header
PCB	3.4" x 2.1"	6 layers
Indicators	1-Power, 2-Ethernet, 4-User Controllable LEDs	
HS USB 2.0 Client Port	Access to USB0, Client mode via miniUSB	
HS USB 2.0 Host Port	Access to USB1, Type A Socket, 500mA LS/FS/HS	
Serial Port	UART0 access via 6 pin 3.3V TTL Header. Header is populated	
Ethernet	10/100, RJ45	
SD/MMC Connector	microSD , 3.3V	
User Input	Reset Button Boot Button Power Button	
Video Out	16b HDMI, 1280x1024 (MAX) 1024x768,1280x720,1440x900 ,1920x1080@24Hz w/EDID Support	
Audio	Via HDMI Interface, Stereo	
Expansion Connectors	Power 5V, 3.3V , VDD_ADC(1.8V) 3.3V I/O on all signals McASP0, SPI1, I2C, GPIO(69 max), LCD, GPMC, MMC1, MMC2, 7 AIN(1.8V MAX), 4 Timers, 4 Serial Ports, CAN0, EHRPWM(0,2),XDMA Interrupt, Power button, Expansion Board ID (Up to 4 can be stacked)	
Weight	1.4 oz (39.68 grams)	
Power	Refer to Section 6.1.7	

Expansion Header P8 Pinout

PIN	PROC	NAME	MODE0	MODE1	MODE2	MODE3	MODE4	MODE5	MODE6	MODE7
1,2						GND				
3	R9	GPIO1_6	gpmc_ad6	mmc1_dat6						gpio1[6]
4	T9	GPIO1_7	gpmc_ad7	mmc1_dat7						gpio1[7]
5	R8	GPIO1_2	gpmc_ad2	mmc1_dat2						gpio1[2]
6	T8	GPIO1_3	gpmc_ad3	mmc1_dat3						gpio1[3]
7	R7	TIMER4	gpmc_advn_ale		timer4					gpio2[2]
8	T7	TIMER7	gpmc_oen_ren		timer7					gpio2[3]
9	T6	TIMER5	gpmc_be0n_cle		timer5					gpio2[5]
10	U6	TIMER6	gpmc_wen		timer6					gpio2[4]
11	R12	GPIO1_13	gpmc_ad13	lcd_data18	mmc1_dat5	mmc2_dat1	eQEP2B_in		pr1_pru0_pru_r30_15	gpio1[13]
12	T12	GPIO1_12	gpmc_ad12	Lcd_data19	mmc1_dat4	Mmc2_dat0	Eqep2a_in		pr1_pru0_pru_r30_14	gpio1[12]
13	T10	EHRPWM2B	gpmc_ad9	lcd_data22	mmc1_dat1	mmc2_dat5	ehrpwm2B			gpio0[23]
14	T11	GPIO0_26	gpmc_ad10	lcd_data21	mmc1_dat2	mmc2_dat6	ehrpwm2_tripzone_in			gpio0[26]
15	U13	GPIO1_15	gpmc_ad15	lcd_data16	mmc1_dat7	mmc2_dat3	eQEP2_strobe		pr1_pru0_pru_r31_15	gpio1[15]
16	V13	GPIO1_14	gpmc_ad14	lcd_data17	mmc1_dat6	mmc2_dat2	eQEP2_index		pr1_pru0_pru_r31_14	gpio1[14]
17	U12	GPIO0_27	gpmc_ad11	lcd_data20	mmc1_dat3	mmc2_dat7	ehrpwm0_synco			gpio0[27]
18	V12	GPIO2_1	gpmc_clk_mux0	lcd_memory_clk	gpmc_wait1	mmc2_clk			mcasp0_fsr	gpio2[1]
19	U10	EHRPWM2A	gpmc_ad8	lcd_data23	mmc1_dat0	mmc2_dat4	ehrpwm2A			gpio0[22]
20	V9	GPIO1_31	gpmc_csn2	gpmc_be1n	mmc1_cmd			pr1_pru1_pru_r30_13	pr1_pru1_pru_r31_13	gpio1[31]
21	U9	GPIO1_30	gpmc_csn1	gpmc_clk	mmc1_clk			pr1_pru1_pru_r30_12	pr1_pru1_pru_r31_12	gpio1[30]
22	V8	GPIO1_5	gpmc_ad5	mmc1_dat5						gpio1[5]
23	U8	GPIO1_4	gpmc_ad4	mmc1_dat4						gpio1[4]
24	V7	GPIO1_1	gpmc_ad1	mmc1_dat1						gpio1[1]
25	U7	GPIO1_0	gpmc_ad0	mmc1_dat0						gpio1[0]
26	V6	GPIO1_29	gpmc_csn0							gpio1[29]
27	U5	GPIO2_22	lcd_vsync	gpmc_a8				pr1_pru1_pru_r30_8	pr1_pru1_pru_r31_8	gpio2[22]
28	V5	GPIO2_24	lcd_pclk	gpmc_a10				pr1_pru1_pru_r30_10	pr1_pru1_pru_r31_10	gpio2[24]
29	R5	GPIO2_23	lcd_hsync	gpmc_a9				pr1_pru1_pru_r30_9	pr1_pru1_pru_r31_9	gpio2[23]
30	R6	GPIO2_25	lcd_ac_bias_en	gpmc_a11						gpio2[25]
31	V4	UART5_CTSN	lcd_data14	gpmc_a18	eQEP1_index	mcasp0_axr1	uart5_rxd		uart5_ctsn	gpio0[10]
32	T5	UART5_RTSN	lcd_data15	gpmc_a19	eQEP1_strobe	mcasp0_ahclkx	mcasp0_axr3		uart5_rtsn	gpio0[11]
33	V3	UART4_RTSN	lcd_data13	gpmc_a17	eQEP1B_in	mcasp0_fsr	mcasp0_axr3		uart4_rtsn	gpio0[9]
34	U4	UART3_RTSN	lcd_data11	gpmc_a15	ehrpwm1B	mcasp0_ahclkr	mcasp0_axr2		uart3_rtsn	gpio2[17]
35	V2	UART4_CTSN	lcd_data12	gpmc_a16	eQEP1A_in	mcasp0_aclkr	mcasp0_axr2		uart4_ctsn	gpio0[8]
36	U3	UART3_CTSN	lcd_data10	gpmc_a14	ehrpwm1A	mcasp0_axr0			uart3_ctsn	gpio2[16]
37	U1	UART5_TXD	lcd_data8	gpmc_a12	ehrpwm1_tripzone_in	mcasp0_aclkx	uart5_txd		uart2_ctsn	gpio2[14]
38	U2	UART5_RXD	lcd_data9	gpmc_a13	ehrpwm0_synco	mcasp0_fsx	uart5_rxd		uart2_rtsn	gpio2[15]
39	T3	GPIO2_12	lcd_data6	gpmc_a6		eQEP2_index		pr1_pru1_pru_r30_6	pr1_pru1_pru_r31_6	gpio2[12]
40	T4	GPIO2_13	lcd_data7	gpmc_a7		eQEP2_strobe	pr1_edio_data_out7	pr1_pru1_pru_r30_7	pr1_pru1_pru_r31_7	gpio2[13]
41	T1	GPIO2_10	lcd_data4	gpmc_a4		eQEP2A_in		pr1_pru1_pru_r30_4	pr1_pru1_pru_r31_4	gpio2[10]
42	T2	GPIO2_11	lcd_data5	gpmc_a5		eQEP2B_in		pr1_pru1_pru_r30_5	pr1_pru1_pru_r31_5	gpio2[11]
43	R3	GPIO2_8	lcd_data2	gpmc_a2		ehrpwm2_tripzone_in		pr1_pru1_pru_r30_2	pr1_pru1_pru_r31_2	gpio2[8]
44	R4	GPIO2_9	lcd_data3	gpmc_a3		ehrpwm0_synco		pr1_pru1_pru_r30_3	pr1_pru1_pru_r31_3	gpio2[9]
45	R1	GPIO2_6	lcd_data0	gpmc_a0		ehrpwm2A		pr1_pru1_pru_r30_0	pr1_pru1_pru_r31_0	gpio2[6]
46	R2	GPIO2_7	lcd_data1	gpmc_a1		ehrpwm2B		pr1_pru1_pru_r30_1	pr1_pru1_pru_r31_1	gpio2[7]

Expansion Header P9 Pinout

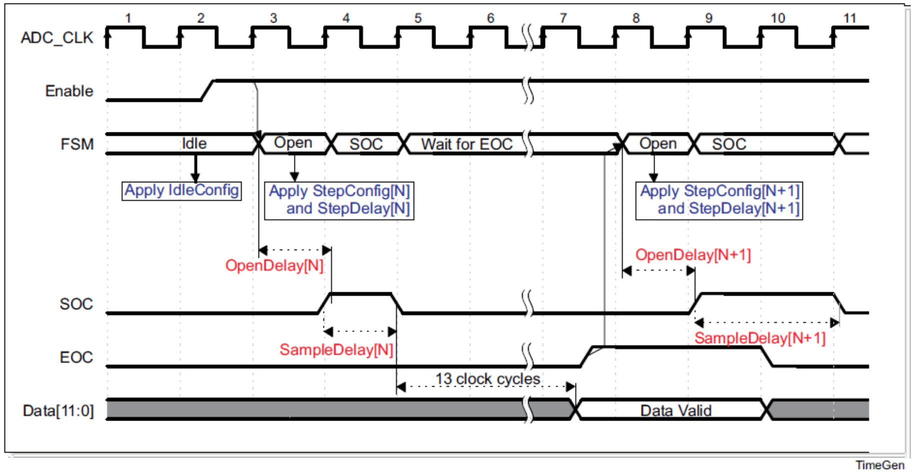
PIN	PROC	NAME	MODE0	MODE1	MODE2	MODE3	MODE4	MODE5	MODE6	MODE7
1,2						GND				
3,4						DC_3.3V				
5,6						VDD_5V				
7,8						SYS_5V				
9						PWR_BUT				
10	A10					SYS_RESETn				
11	T17	UART4_RXD	gpmc_wait0	mii2_crs	gpmc_csn4	rmii2_crs_dv	mmc1_sdcd		uart4_rxd_mux2	gpio0[30]
12	U18	GPIO1_28	gpmc_be1n	mii2_col	gpmc_csn6	mmc2_dat3	gpmc_dir		mcasp0_aclkr_mux3	gpio1[28]
13	U17	UART4_TXD	gpmc_wpn	mii2_rxerr	gpmc_csn5	rmii2_rxerr	mmc2_sdcd		uart4_txd_mux2	gpio0[31]
14	U14	EHRPWM1A	gpmc_a2	mii2_txd3	rgmii2_td3	mmc2_dat1	gpmc_a18		ehrpwm1A_mux1	gpio1[18]
15	R13	GPIO1_16	gpmc_a0	gmii2_txen	rmii2_tctl	mii2_txen	gpmc_a16		ehrpwm1_tripzone_input	gpio1[16]
16	T14	EHRPWM1B	gpmc_a3	mii2_txd2	rgmii2_td2	mmc2_dat2	gpmc_a19		ehrpwm1B_mux1	gpio1[19]
17	A16	I2C1_SCL	spi0_cs0	mmc2_sdwp	I2C1_SCL	ehrpwm0_synci	pr1_uart0_txd			gpio0[5]
18	B16	I2C1_SDA	spi0_d1	mmc1_sdwp	I2C1_SDA	ehrpwm0_tripzone	pr1_uart0_rxd			gpio0[4]
19	D17	I2C2_SCL	uart1_rtsn	timer5	dcan0_rx	I2C2_SCL	spi1_cs1	pr1_uart0_rts_n		gpio0[13]
20	D18	I2C2_SDA	uart1_ctsn	timer6	dcan0_tx	I2C2_SDA	spi1_cs0	pr1_uart0_cts_n		gpio0[12]
21	B17	UART2_TXD	spi0_d0	uart2_txd	I2C2_SCL	ehrpwm0B	pr1_uart0_rts_n		EMU3_mux1	gpio0[3]
22	A17	UART2_RXD	spi0_sclk	uart2_rxd	I2C2_SDA	ehrpwm0A	pr1_uart0_cts_n		EMU2_mux1	gpio0[2]
23	V14	GPIO1_17	gpmc_a1	gmii2_rxdv	rgmii2_rxdv	mmc2_dat0	gpmc_a17		ehrpwm0_synco	gpio1[17]
24	D15	UART1_TXD	uart1_txd	mmc2_sdwp	dcan1_rx	I2C1_SCL		pr1_uart0_txd	pr1_pru0_pru_r31_16	gpio0[15]
25	A14	GPIO3_21*	mcasp0_ahclkx	eQEP0_strobe	mcasp0_axr3	mcasp1_axr1	EMU4_mux2	pr1_pru0_pru_r30_7	pr1_pru0_pru_r31_7	gpio3[21]
26	D16	UART1_RXD	uart1_rxd	mmc1_sdwp	dcan1_tx	I2C1_SDA		pr1_uart0_rxd	pr1_pru1_pru_r31_16	gpio0[14]
27	C13	GPIO3_19	mcasp0_fsr	eQEP0B_in	mcasp0_axr3	mcasp1_fsx	EMU2_mux2	pr1_pru0_pru_r30_5	pr1_pru0_pru_r31_5	gpio3[19]
28	C12	SPI1_CS0	mcasp0_ahclkr	ehrpwm0_synci	mcasp0_axr2	spi1_cs0	eCAP2_in_PWM2_out	pr1_pru0_pru_r30_3	pr1_pru0_pru_r31_3	gpio3[17]
29	B13	SPI1_D0	mcasp0_fsx	ehrpwm0B		spi1_d0	mmc1_sdcd_mux1	pr1_pru0_pru_r30_1	pr1_pru0_pru_r31_1	gpio3[15]
30	D12	SPI1_D1	mcasp0_axr0	ehrpwm0_tripzone		spi1_d1	mmc2_sdcd_mux1	pr1_pru0_pru_r30_2	pr1_pru0_pru_r31_2	gpio3[16]
31	A13	SPI1_SCLK	mcasp0_aclkx	ehrpwm0A		spi1_sclk	mmc0_sdcd_mux1	pr1_pru0_pru_r30_0	pr1_pru0_pru_r31_0	gpio3[14]
32						VADC				
33	C8					AIN4				
34						AGND				
35	A8					AIN6				
36	B8					AIN5				
37	B7					AIN2				
38	A7					AIN3				
39	B6					AIN0				
40	C7					AIN1				
41#	D14	CLKOUT2	xdma_event_intr1		tclkin	clkout2	timer7_mux1	pr1_pru0_pru_r31_16	EMU3_mux0	gpio0[20]
	D13	GPIO3_20	mcasp0_axr1	eQEP0_index		Mcasp1_axr0	emu3	pr1_pru0_pru_r30_6	pr1_pru0_pru_r31_6	gpio3[20]
42@	C18	GPIO0_7	eCAP0_in_PWM0_out	uart3_txd	spi1_cs1	pr1_ecap0_ecap_capin_apwm_o	spi1_sclk	mmc0_sdwp	xdma_event_intr2	gpio0[7]
	B12	GPIO3_18	Mcasp0_aclkr	eQEP0A_in	Mcaspo_axr2	Mcasp1_aclkx		pr1_pru0_pru_r30_4	pr1_pru0_pru_r31_4	gpio3[18]
43-46						GND				

BACKUP: MEASUREMENTS

Measurement Timing

Lidar range and beam attitude measurements shall be taken within one microsecond.

- 15 ADC clocks per sample
  625 ns full conversion
- Reading the quadrature decoder registers may be accomplished in this time (~4 ns)

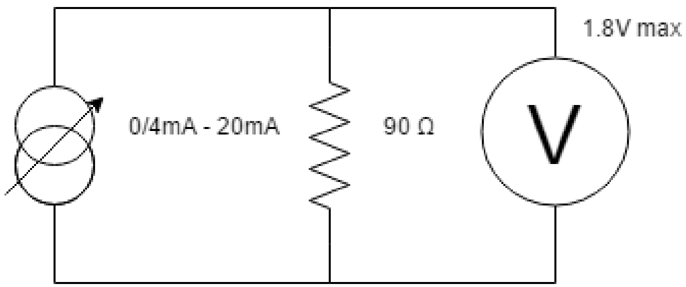


Full measurement time is limited by the ADC

Lidar Measurement

The lidar shall send range data to the on-board processor or DAQ

- The lidar produces a 0/4 mA to 20 mA current loop based off of the range between two set points A and B.
- A 90 ohm resistor is used to turn this into a 1.8 V max signal which is read on the microcontroller's ADC

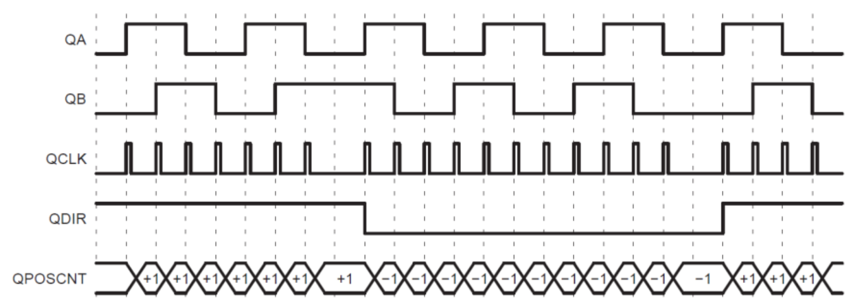


Resolution for a 12 Bit ADC
(15-0.2) m / 2^12 = 3.613 mm

Quadrature Decoding

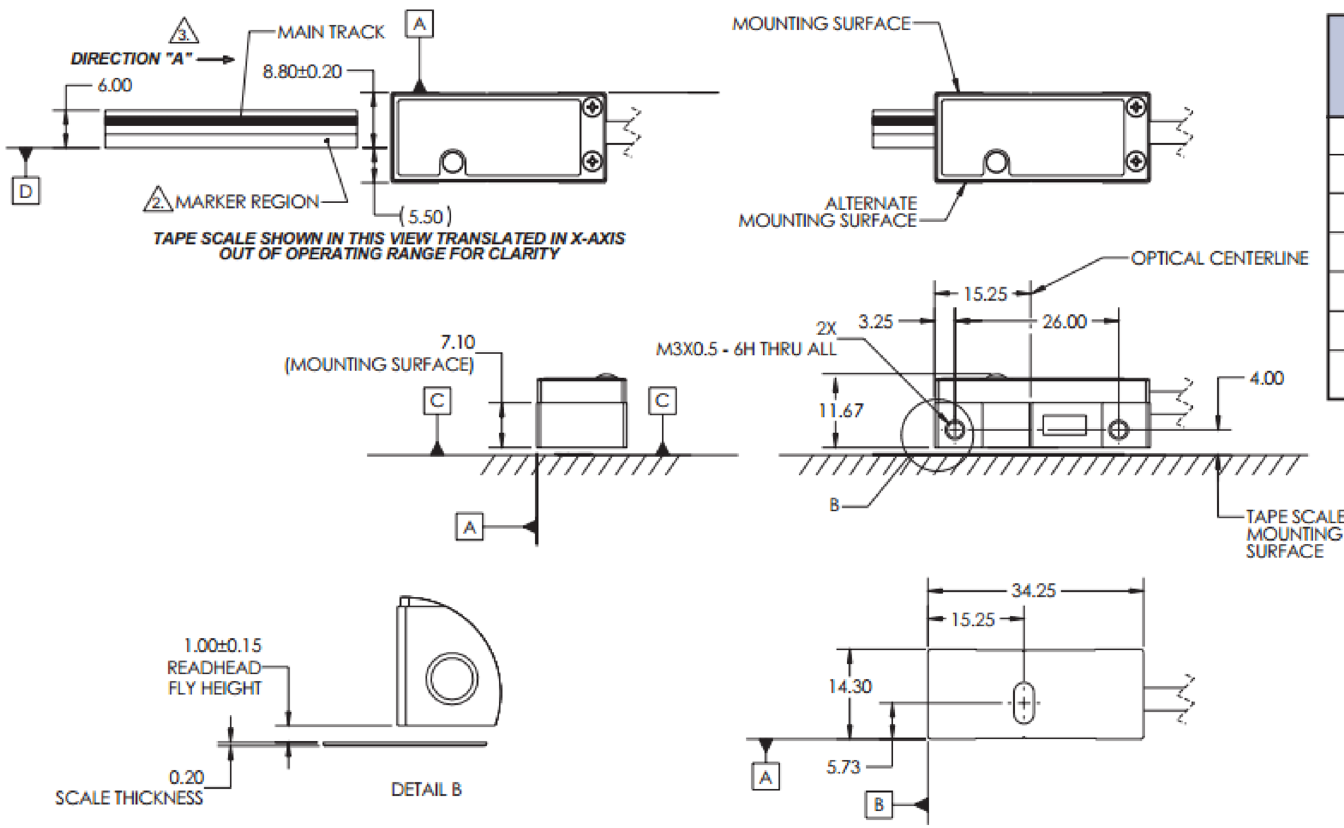
The beam attitude measurement shall be sent to the on-board processor or DAQ.

- The BeagleBone Black has quadrature decoders that interface directly with the OPS optical encoders
- Taking measurements is as simple as reading each counter

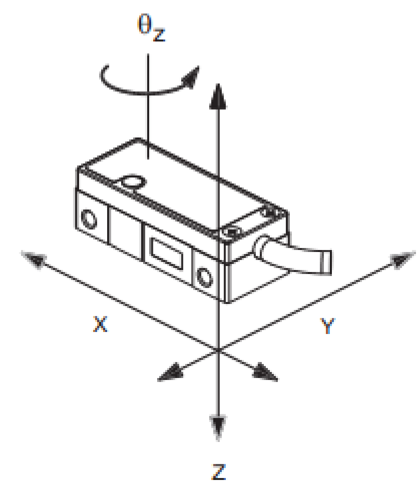


BACKUP: ENCODER INTEGRATION

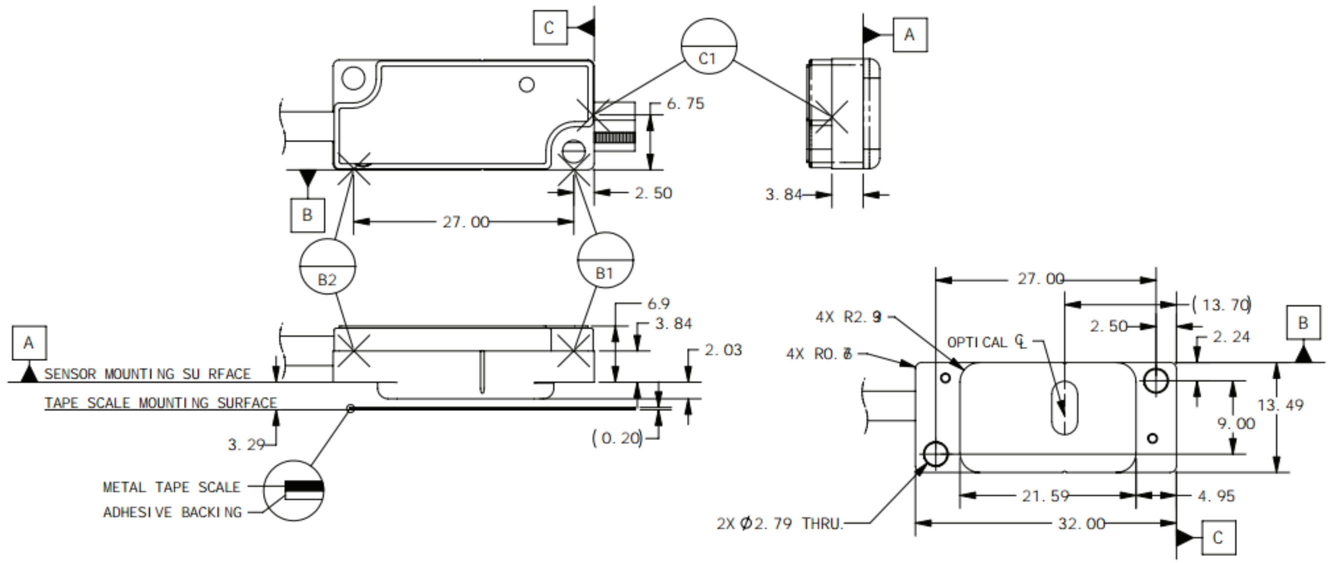
OPS Encoder Mounting Side



OPS Side Mount Configuration Sensor Alignment Tolerances	
Axis	**Alignment Tolerance**
X	Direction of Motion
Y	± 0.20mm
Z	± 0.15mm
θ_X	± 1.0°
θ_Y	± 1.0°
θ_Z	± 2.0°

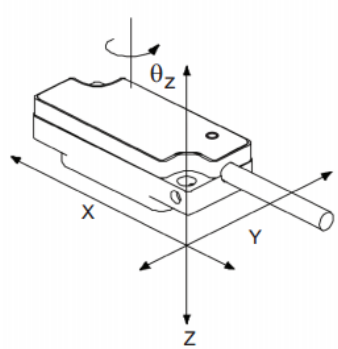


OPS Encoder Mounting Top



Wide Alignment Tolerances

OPS Top Mount Configuration Sensor Alignment Tolerances	
Axis	Alignment Tolerance
X	Direction of Motion
Y	± 0.20mm
Z	± 0.15mm
θ_X	± 1.0°
θ_Y	± 1.0°
θ_Z	± 2.0°



Sensor Size & Weight (top mount sensor)

Height	Width	Length
0.35[8.93mm]	0.53 [13.49mm]	1.26 [32.00mm]
Weight	6g (without cable)	

OPS Encoder Alignment

OPS Alignment Tool.

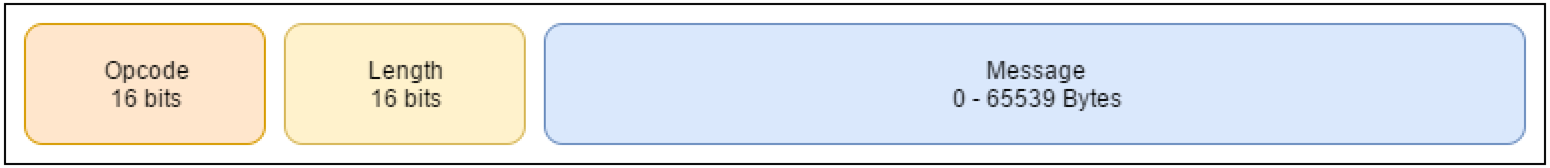
BACKUP: COMMUNICATION

Communication Between Microcontroller and PC

- UART – 115200 bits / sec
- USB 2.0 – 480 Mbits / sec (high speed)
- Ethernet/IP – 10/100/1000 Mbits /sec

Controller-PC communication layer agnostic to protocol

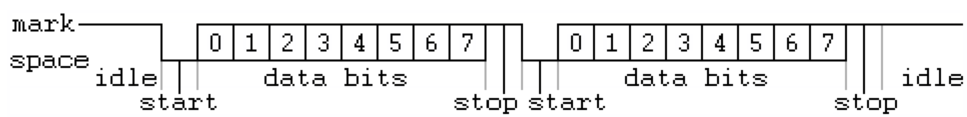
Communication Packet Between PC and BeagleBone
4 to 65539 Bytes



Sample Message Data

UART

- Will require an FTDI
- 115200 bits/s
- 8 data bits per packet
  1 start and 1 stop
- 11520 bytes/s



Ethernet data rate feasibility

IPv4

Max Ethernet packet 1518 bytes

68 bytes of UDP overhead (with IP and Ethernet frames)

1472 bytes left for data → 60 measurements per packet

1512 byte total packet size

100 Mb/s: 8127 frames/sec * 1512 bytes/frame =
12.288 Mbytes/s

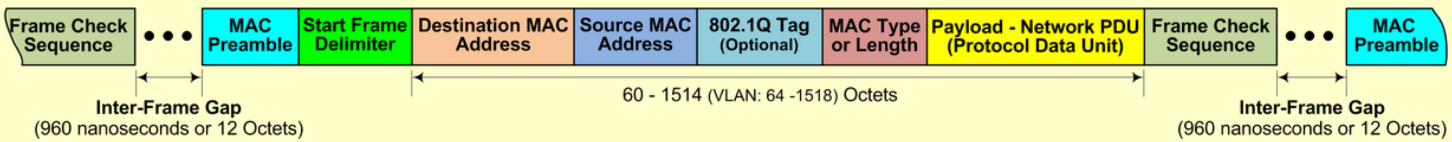
1000 Mb/s: 81274 frames/sec * 1512 bytes/frame =
122.8 Mbytes/s

Ethernet UDP Overhead

Fast Ethernet (IEEE 802.3u) - UDP

Maximum Ethernet frames and data throughput rate calculations.

Fast Ethernet (IEEE 802.3u) Frame Structure with UDP Datagram



Fast Ethernet Frame Component Size With UDP Datagram

Frame Component		Component Size	
MAC Preamble		7 Octets of: **10101010**	
Start Frame Delimiter		1 Octet of: **10101011**	
Destination MAC Address		6 Octets	
Source MAC Address		6 Octets	
802.1Q VLAN TAG ID (Optional)		4 Octets (Optional)	
MAC Type or Length		2 Octets	
MTU (Maximum Transmission Unit) **Payload** Network PDU Protocol Data Unit:	Packet	**IP Header**	20 Octets
	Packet / Segment	**UDP Header**	8 Octets
	Packet / Segment	**Data/Padding**	18 - 1472 Octets
		Total:	**46 - 1500 Octets** (Max: 1504 – VLAN)
Frame Check Sequence (CRC)		4 Octets	
Inter-Frame Gap • • •		12 Octets (960 nanoseconds)	
Total Physical Frame Size:		**84 – 1538 Octets** (Max: 1544 -VLAN)	

Fast Ethernet Maximum Frame and Data Throughput Rate Calculation with UDP Datagram

Rate Term	Value
Fast Ethernet Bit Rate	100 Mbit/sec -or- 100Mb/sec
Fast Ethernet Bit Time	10 nanoseconds (.00000001 seconds)
1 Octet (Byte)	8 Bits
Max Octet Rate	(100Mb/sec)/((8 Bits) = **12,500,000 Octets/sec**
Max Frame Rate (84 Octet Frames) Min Packet (60 Bytes + 4 Bytes CRC)	(100Mb/sec)/((8 Bits)*(84 Octets/Frame)) = **148,810 Frames/sec (FPS)**
Max UDP Data Rate (84 Octet Frames) Min UDP Packet (60 Bytes + 4 Bytes CRC)	(148,810 Frames/sec)*(18 Bytes/Frame) = **2,678,571 Bytes/sec**
Max Frame Rate (1538 Octet Frames) Max Packet (1514 Bytes + 4 Bytes CRC)	(100Mb/sec)/((8 Bits)*(1538 Octets/Frame)) = **8,127 Frames/sec (FPS)**
Max UDP Data Rate (1538 Octet Frames) Max UDP Packet (1514 Bytes + 4 Bytes CRC)	(8,127 Frames/sec)*(1472 Bytes/Frame) = **11,963,589 Bytes/sec**
Max Fast Ethernet Frame Bandwidth Max Packet (60 Bytes + 4 Bytes CRC) Max Packet (60 Bytes)	(148,810 Frames/sec)*(64 Bytes/Frame) = **9,523,840 Bytes/sec** (9.082641 MiB/s) (148,810 Frames/sec)*(60 Bytes/Frame) = **8,928,600 Bytes/sec** (8.514977 MiB/s)
Max Fast Ethernet Frame Bandwidth Max Packet (1514 Bytes + 4 Bytes CRC) Max Packet (1514 Bytes)	(8,127 Frames/sec)*(1518 Bytes/Frame) = **12,336,786 Bytes/sec** (11.765276 MiB/s) (8,127 Frames/sec)*(1514 Bytes/Frame) = **12,304,278 Bytes/sec** (11.734274 MiB/s)

*** **Note 1:** Units – **M:** 1,000,000 **Mi:** 1,048,576

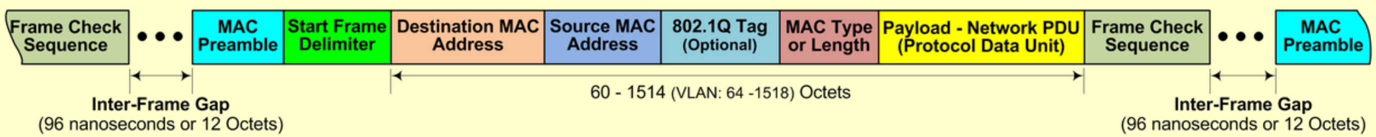
NST - 2011

Ethernet UDP Overhead

Gigabit Ethernet (IEEE 802.3ab) - UDP

Maximum Ethernet frames and data throughput rate calculations.

Gigabit Ethernet (IEEE 802.3ab) Frame Structure with UDP Datagram



Gigabit Ethernet Frame Component Size With UDP Datagram

Frame Component	Component Size	
MAC Preamble	7 Octets of: **10101010**	
Start Frame Delimiter	1 Octet of: **10101011**	
Destination MAC Address	6 Octets	
Source MAC Address	6 Octets	
802.1Q VLAN TAG ID (Optional)	4 Octets (Optional)	
MAC Type or Length	2 Octets	
MTU (Maximum Transmission Unit) / Packet / Segment / **Payload** Network PDU Protocol Data Unit:	IP Header	20 Octets
	UDP Header	8 Octets
	Data/Padding	18 - 1472 Octets
	***Total:	**46 - 1500 Octets** (Max: 1504 – VLAN)
Frame Check Sequence (CRC)	4 Octets	
Inter-Frame Gap • • •	12 Octets (96 nanoseconds)	
Total Physical Frame Size:	**84 – 1538 Octets** (Max: 1544 -VLAN)	

Gigabit Ethernet Maximum Frame and Data Throughput Rate Calculation with UDP Datagram

Rate Term	Value
Gigabit Ethernet Bit Rate	1000 Mbit/sec -or- 1000Mb/sec
Gigabit Ethernet Bit Time	1 nanosecond (.000000001 seconds)
1 Octet (Byte)	8 Bits
Max Octet Rate	(1000Mb/sec)/((8 Bits) = **125,000,000 Octets/sec**
Max Frame Rate (84 Octet Frames) Min Packet (60 Bytes + 4 Bytes CRC)	(1000Mb/sec)/((8 Bits)*(84 Octets/Frame)) = **1,488,095 Frames/sec (FPS)**
Max UDP Data Rate (84 Octet Frames) Min UDP Packet (60 Bytes + 4 Bytes CRC)	(1,488,095 Frames/sec)*(18 Bytes/Frame) = **26,785,714 Bytes/sec**
Max Frame Rate (1538 Octet Frames) Max Packet (1514 Bytes + 4 Bytes CRC)	(1000Mb/sec)/((8 Bits)*(1538 Octets/Frame)) = **81,274 Frames/sec (FPS)**
Max UDP Data Rate (1538 Octet Frames) Max UDP Packet (1514 Bytes + 4 Bytes CRC)	(81,274 Frames/sec)*(1472 Bytes/Frame) = **119,635,891 Bytes/sec**
Max Gigabit Ethernet Frame Bandwidth Max Packet (60 Bytes + 4 Bytes CRC) Max Packet (60 Bytes)	(1,488,095 Frames/sec)*(64 Bytes/Frame) = **95,238,080 Bytes/sec** (90.876031 MiB/s) (1,488,095 Frames/sec)*(60 Bytes/Frame) = **89,285,700 Bytes/sec** (85.149477 MiB/s)
Max Gigabit Ethernet Frame Bandwidth Max Packet (1514 Bytes + 4 Bytes CRC) Max Packet (1514 Bytes)	(81,274 Frames/sec)*(1518 Bytes/Frame) = **123,373,932 Bytes/sec** (117.658550 MiB/s) (81,274 Frames/sec)*(1514 Bytes/Frame) = **123,048,836 Bytes/sec** (117.348515 MiB/s)

*** **Note 1:** IEEE 802.3ab – Gigabit Ethernet over copper twisted-pair cabling.
*** **Note 2:** Gigabit Ethernet allows for larger MTUs (Jumbo or Super Jumbo Frames).
*** **Note 3:** Units – **M:** 1,000,000 **Mi:** 1,048,576

NST - 2011

USB Data Rate Feasibility

- **Universal Serial Bus Specification Revision 2.0**

Table 5-10. High-speed Bulk Transaction Limits

	Protocol Overhead (55 bytes)		(3x4 SYNC bytes, 3 PID bytes, 2 EP/ADDR+CRC bytes, 2 CRC16, and a 3x(1+11) byte interpacket delay (EOP, etc.))			
	Data Payload	**Max Bandwidth (bytes/second)**	**Microframe Bandwidth per Transfer**	**Max Transfers**	**Bytes Remaining**	**Bytes/ Microframe Useful Data**
	1	1064000	1%	133	52	133
	2	2096000	1%	131	33	262
	4	4064000	1%	127	7	508
	8	7616000	1%	119	3	952
	16	13440000	1%	105	45	1680
	32	22016000	1%	86	18	2752
	64	32256000	2%	63	3	4032
	128	40960000	2%	40	180	5120
	256	49152000	4%	24	36	6144
	512	53248000	8%	13	129	6656
Max		60000000				7500

21 measurements for the maximum data payload produces a 508-byte data payload

Speeds should be over 50 million bytes a second

USB 2.0

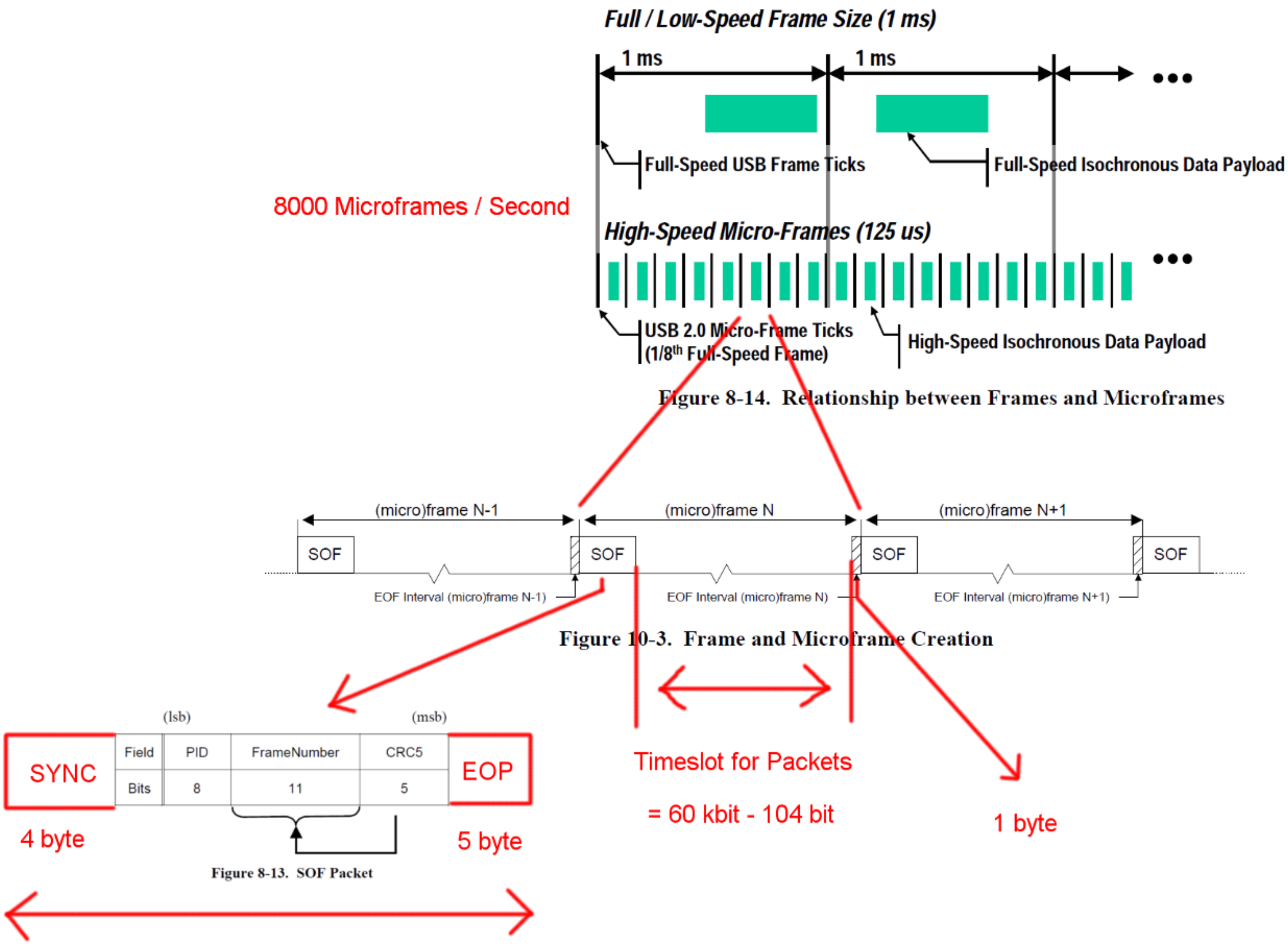
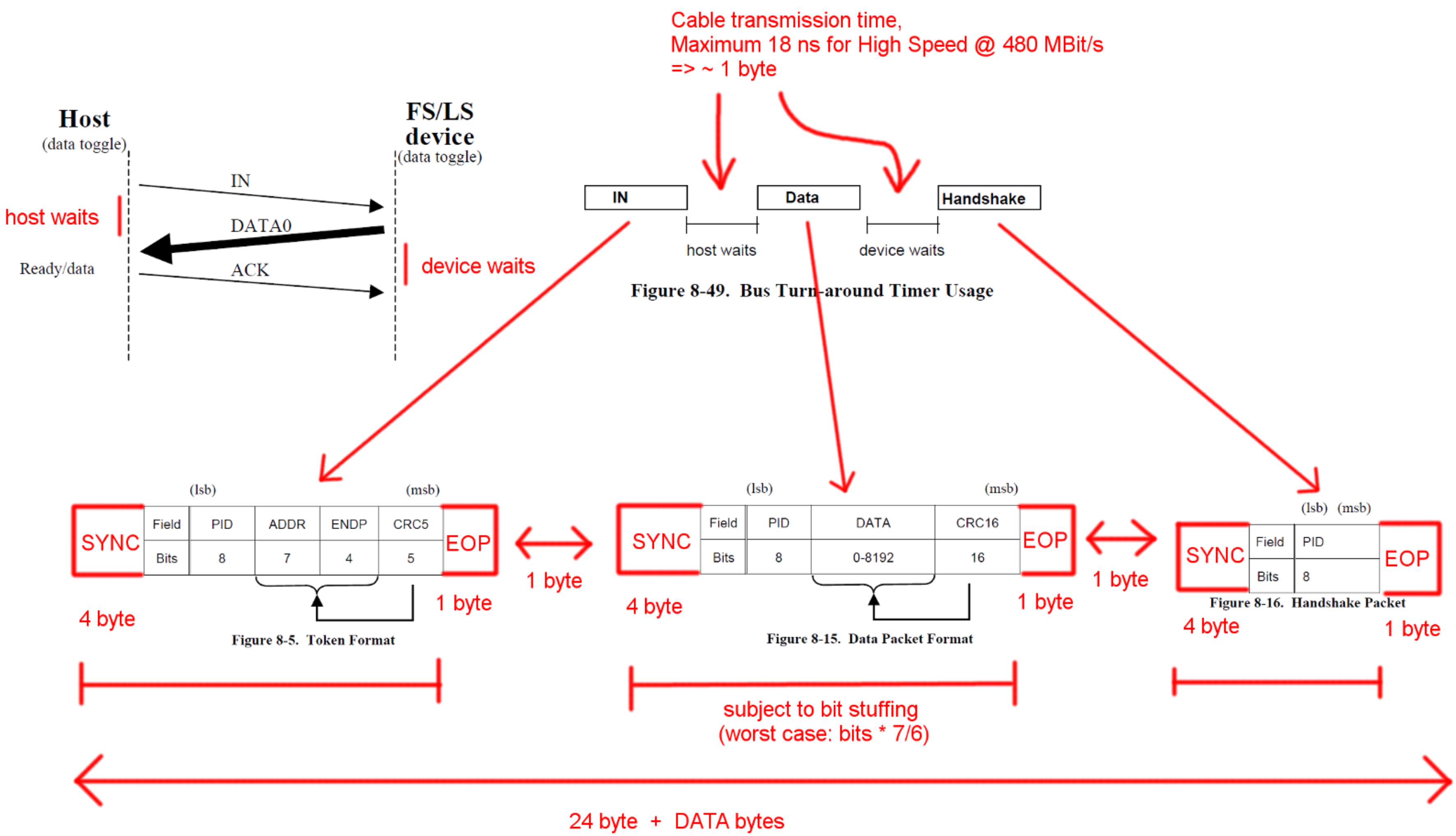


Figure 8-14. Relationship between Frames and Microframes

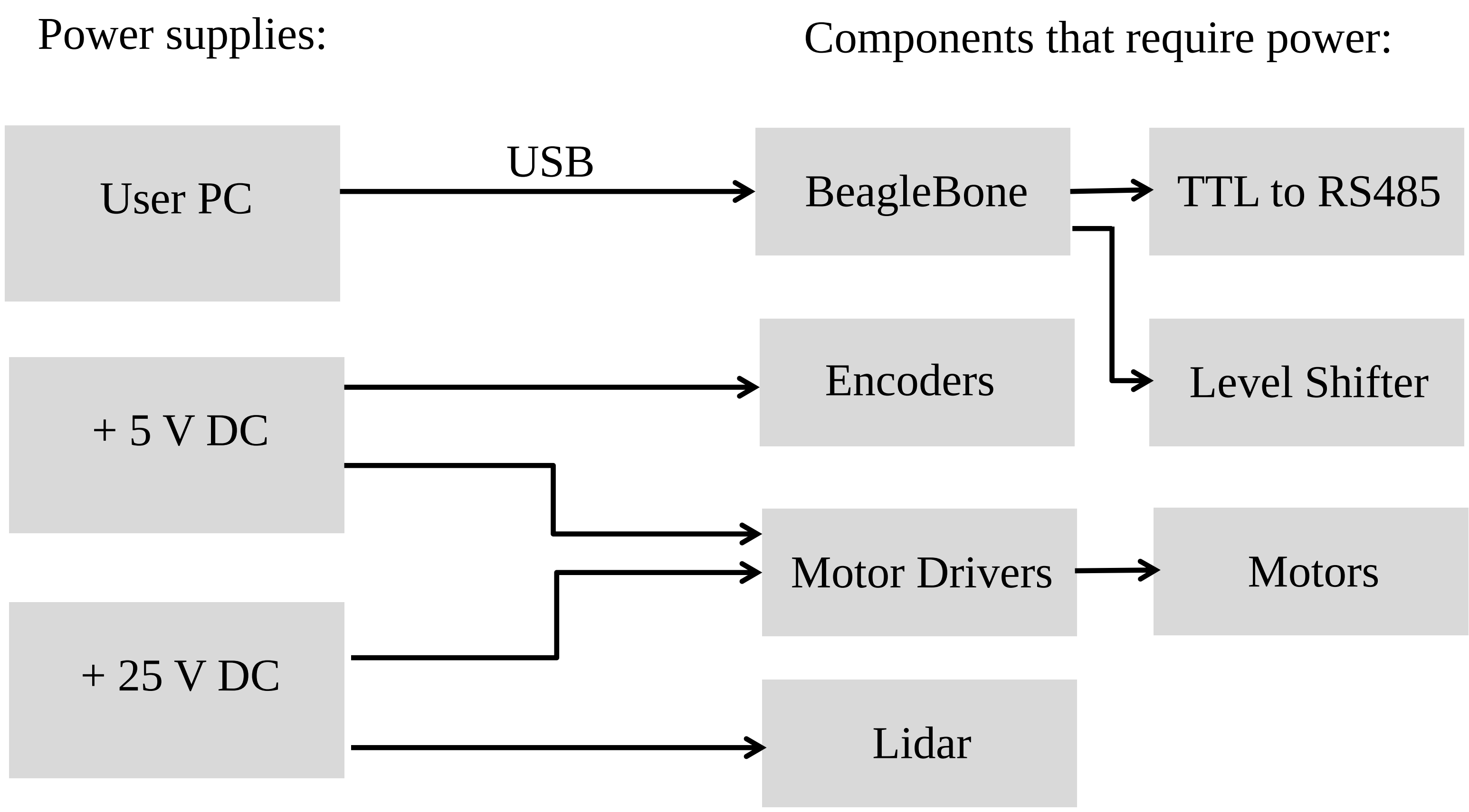
Figure 10-3. Frame and Microframe Creation

Figure 8-13. SOF Packet

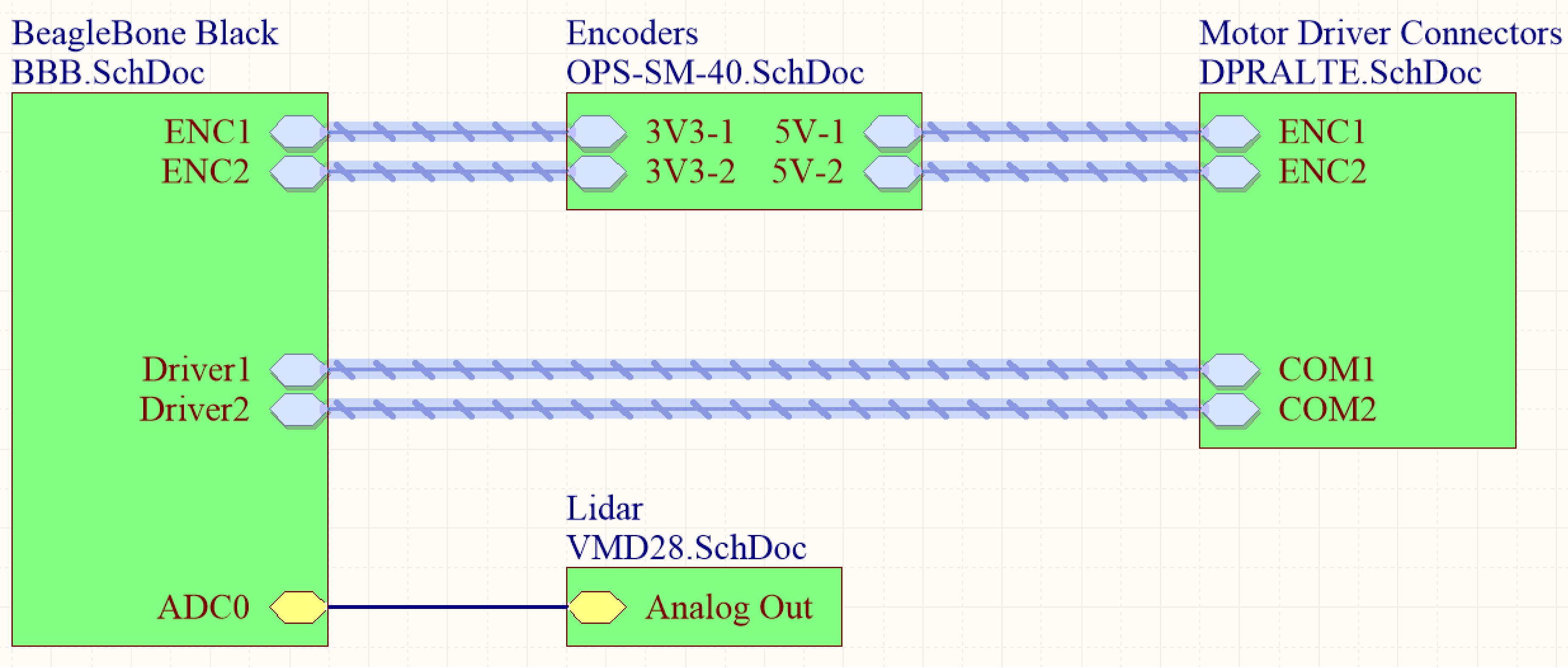
USB 2.0


Cable transmission time,
Maximum 18 ns for High Speed @ 480 MBit/s
=> ~ 1 byte
Host
(data toggle)
FS/LS device
(data toggle)
host waits
IN
DATA0
Ready/data
ACK
device waits
IN
Data
Handshake
host waits
device waits
Figure 8-49. Bus Turn-around Timer Usage
(lsb)
(msb)
SYNC
Field
PID
ADDR
ENDP
CRC5
Bits
8
7
4
5
EOP
4 byte
1 byte
Figure 8-5. Token Format
1 byte
SYNC
Field
PID
DATA
CRC16
Bits
8
0-8192
16
EOP
4 byte
1 byte
Figure 8-15. Data Packet Format
1 byte
SYNC
Field
PID
Bits
8
EOP
Figure 8-16. Handshake Packet
4 byte
1 byte
subject to bit stuffing
(worst case: bits * 7/6)
24 byte + DATA bytes

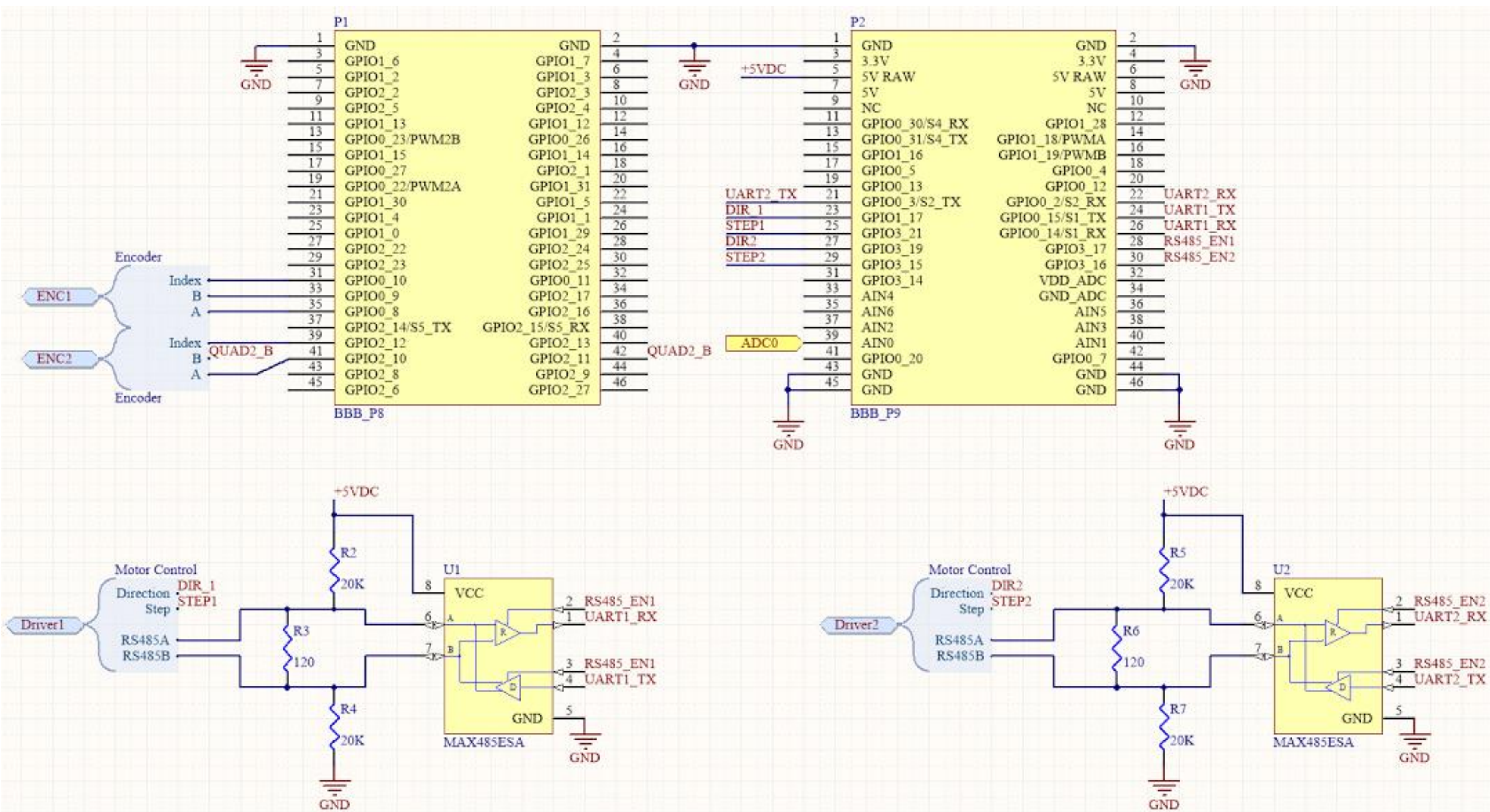
Power


Power supplies:
Components that require power:
User PC
USB
BeagleBone
TTL to RS485
Encoders
Level Shifter
+ 5 V DC
Motor Drivers
Motors
+ 25 V DC
Lidar

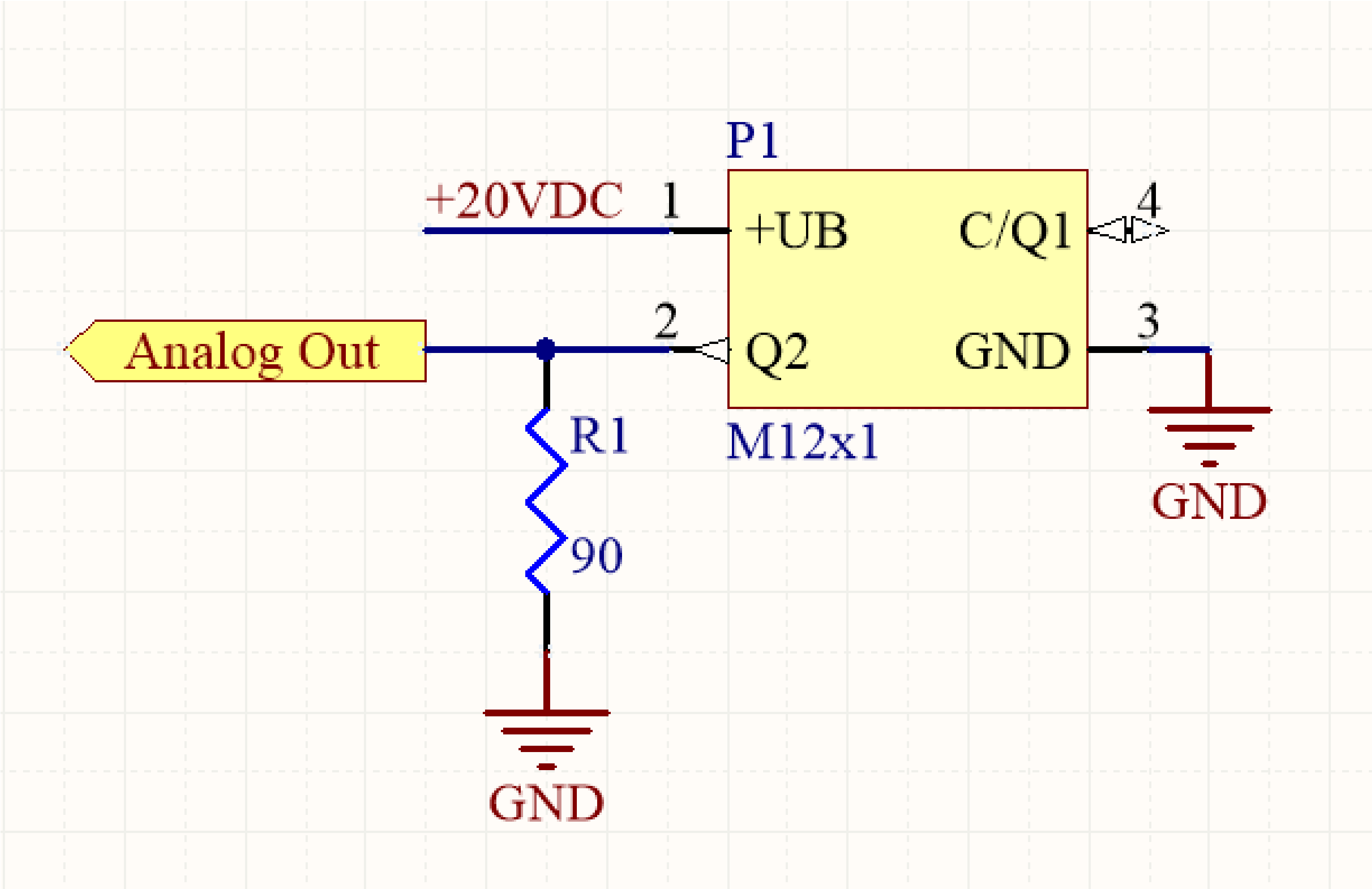
Top Level Connections



BeagleBone Connections



Lidar Connections



BACKUP: VERIFICATION AND VALIDATION

Artec Eva Lite 3D Scanner

<u>Specifications</u>

- 3D resolution: 0.5 mm
- 3D point accuracy: 0.1 mm

<u>Output</u>

- Creates a SOLIDWORKS file of the scanned object/surface

Scan Pattern Feasibility

Solution: Perform two system-level tests:

1. Verify that the sensor package can obtain measurements with the required resolution in a longer period of time
2. Verify the ability of the system to perform a 60-second scan/analysis, even though the required resolution cannot be met

Resolution requirement test:

- Lidar frequency: 100 Hz
- Point spacing (exterior): 2.5 cm
- Exterior spiral arc length: 32.32 m
- Time to complete scan: ~12 min
- Maximum prism angular acceleration
- Required angular velocity: **4.6536 rpm**
- Maximum prism angular acceleration: 4.8e-6 rad/s^2

Time requirement test:

- Spiral spacing of 8.66 cm gives 59 total spirals
- Time: 50 seconds (leaving margin for analysis)
- Required lidar frequency: 382 Hz
- Required angular velocity: **71.0763 rpm**
- Maximum prism angular acceleration: 3.76e-6 rad/s^2

Test Setup (Lidar)

- Receive return through glass
  - Shoot lidar through panes of glass and use oscilloscope to determine if the lidar is receiving a return
- Range, error and precision
  - Over a timespan on 60 sec, consistent measurements with accuracy of +/- 5 cm must be taken
- Reflective tape
  - Measure signal return accuracy, consistency, and strength from surface with and without retro-reflective tape
- Sample Frequency
  - Using an oscilloscope, determine time (in milliseconds) between range measurements

Test Setup (Prisms)

- Must be able to turn beam 20°
  - Mount prisms parallel to lidar, manually rotate prisms and verify 20° beam divergence
- Returns through glass
  - If the lidar does not receive returns through glass, replace the glass with coated prisms and repeat trials

Test Setup (Encoders)

- Determine functionality of hardware
  - Connect encoders to microprocessor and motors
  - Manually move motor to verify functionality of encoders
    - This is just to test connectivity and verify that communication is working properly

Test Setup (Motors)

- Motor functionality
  - Connect motors to motor drivers and provide any arbitrary commands, verify response happens
- All required motor rates must be achievable
  - Once motor, encoder, driver, and microprocessor system is fully integrated
  - Command to maximum rate of 71 rpm and hold for 50 sec
  - Command to minimum rate of 4 rpm and hold for 13 min
- Time to accelerate to desired motor rates
  - Given motor rate commands, verify motor accelerations are within desired bounds from encoder output analysis

Test Setup (Motor Drivers)

- Given any input the drivers must change the position of the motors
  - This can be visually verified
- Verify that command accuracy of 0.1° can be met
  - Can verify commanded vs actual by manually comparing commanded angle and actual angle
  - Can more accurately verify by comparing computational models of prism rotation, given a single motor angle displacement, against encoder positions
    - Measuring initial and final laser position physically and predictively in software

Test Setup (Software)

- Unit tests
  - x, y, z coordinate rotation
  - Read in IMU data, prism positions, and range
    - Combine to produce range measurement
  - Actual hazard output should match expected
    - Expected generated by software mockup
  - Generate health and status reports
  - Output results

Full Budget

Item	Quantity	Cost per (USD)	Total Discounts (USD)	Total cost (USD)	Source/Notes
Lidar:					
Pepperl-Fuchs VDM28-15-L-IO/73c/110/122	1	470.17	470.17	0	https://www.carltonbates.com/Photoelectric-Sensors-Reflex-Reflective-Block-Style-/PEPPE
Motors:					
ULT-165-A-12-A-x-00x	1	1033		1033	Requested quote from "http://www.celeramotion.com/"
Encoders:					
OPS read head (OD 3.937" ID 2.756")	2	560		1120	Requested quote from "http://www.celeramotion.com/"
Bearings:					
VA030CP0 Thin Section Bearing 3"x3 1/2"x1/4" inch Open	4	81.77		327.08	http://www.vxb.com/VA030CP0-Thin-Section-3-x3-1-2-x1-4-inch-Open-p/kit8779.htm
Microprocessor:					
BeagleBone Black Rev C.1	1	55		55	https://www.adafruit.com/products/1996
Reflective Tape					
Oralite (Reflexite) R99 Rail Microprismatic Retroreflective Conspicuity Tape: 4 in. x 15 ft. (White)	9	36.22		325.98	https://www.amazon.com/gp/product/B00420CDOK/ref=s9_simh_gw_g469_i4_r?ie=UTF8
Motor Drivers:					
DPRALTE - 020B080	2	605	363	847	https://www.servo2go.com/product.php?ID=101890#details
Risley prism:					
P-WRC059 coated with BBAR 400-700 nm	2	108		216	Requested quote from "http://www.rossoptical.com/"
Materials					
Mat: misc electronics				300	
Mat: Fasteners				166	
Mat: Stock				849.77	
Mat: Tooling				812	can increase to 922 if budget provides, buying additional tools for arsenl
Shipping				330	Assuming $15 per item
Total (Cost)				**6381.83**	Tax exempt
Budget				5000	Provided by the CU Aerospace Engineering department
				1000	UROP Funding
				2300	Thayer
Total (Budget)				**8300**	
Percent Margin				**23.11048193**	

Full Budget: Materials

Part	Mat	Shape	H	L / diameter	W	Stock Dims	Cost	Quantity	Total	All from mcmaster
Base Plate	Al 6061	Plate	0.625	10	8	.625x12x12	74.9	1	149.8	
Lidar Stand	Al 6061	Block	2.992	3.75	2.5	3x3.5x6	53.5	1	53.5	
Side Bracket	Al 6061	Plate	0.5	3.32	2.25	.5x3x6	68.1	2	136.2	
Top Bracket	Al 6061	Plate	0.125	3.32	3	.125x4x6	60.19	1	60.19	
Outside Bracket	Al 6061	Plate	0.402	7	7	.438x8x8	32.86	2	65.72	
Main Housing	Al 6061	Plate	1.3	7	7	1.5x8x8	71.12	2	142.24	
Bearing Clamp	Al 6061	Cyl	0.163	4.25		4.75x0.5	11.32	2	22.64	
Prism Enclosure	Al 6061	Cyl	0.625	3.125		3.25x1	9.34	2	18.68	
Rotor	Al 6061	Cyl	0.523	5		6x.75	77.2	2	154.4	
Encoder Hub	304 SS	Cyl	0.188	3.272		3.5x.5	23.2	2	46.4	
									849.77	Total (USD)

Screws	Quantity	Cost Per 25	Total	
#2-56	50	7.2	14.4	All from mcmaster
#4-40	50	7.5	15	
#8-32	75	7.63	22.89	
1/4 20	20	7.84	7.84	
			60.13	Total (USD)

Dowel Pin screw equivil	Quantity	Cost Per Pack	Total	
#2-26	10	8.23	8.23	All from mcmaster
#4-40	6	9.79	9.79	
#8-32	6	11.67	11.67	
1/4 20	6	13.13	13.13	
			42.82	Total (USD)

Machining Tools	Quantity	Cost Per	Total	
End Mills	1	186.72	186.72	from mscdirect
Drill Kit	1	100	100	
Edge Finder	1	63.39	63.39	
			350.11	Total (USD)

Cabling	100

GRAND TOTAL (USD)
1402.83