Spring Final Review

Customer:
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BAFFLING BUFFS

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Project Purpose and Objectives

Project Motivation

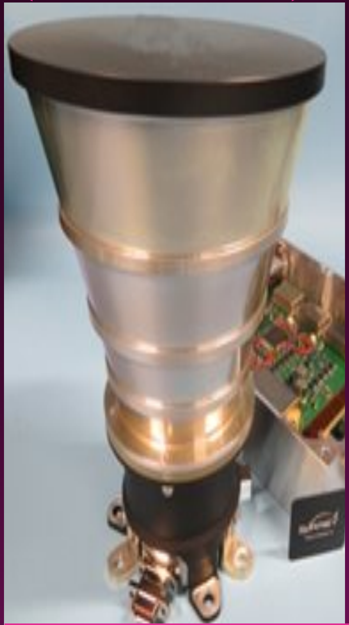
- Star trackers need to see dim light from distant stars
- They compare what they see with onboard star catalog to make spacecraft attitude adjustments
- Nearby bodies emit/reflect stray light which hinders star trackers ability to see dim light
- Baffles attenuate and eliminate stray light from nearby bodies
- Lightweight deployable baffle for smallsats

Comparison

Surrey Procyon Star Tracker Baffle[1]: 0.55 kg

125 mm

165 mm



CU Star Tracker Baffle: 0.26 kg

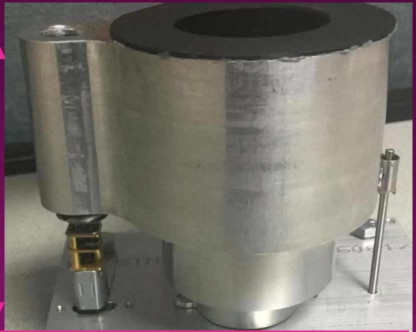
Stowed

50 mm

Deployed

125 mm

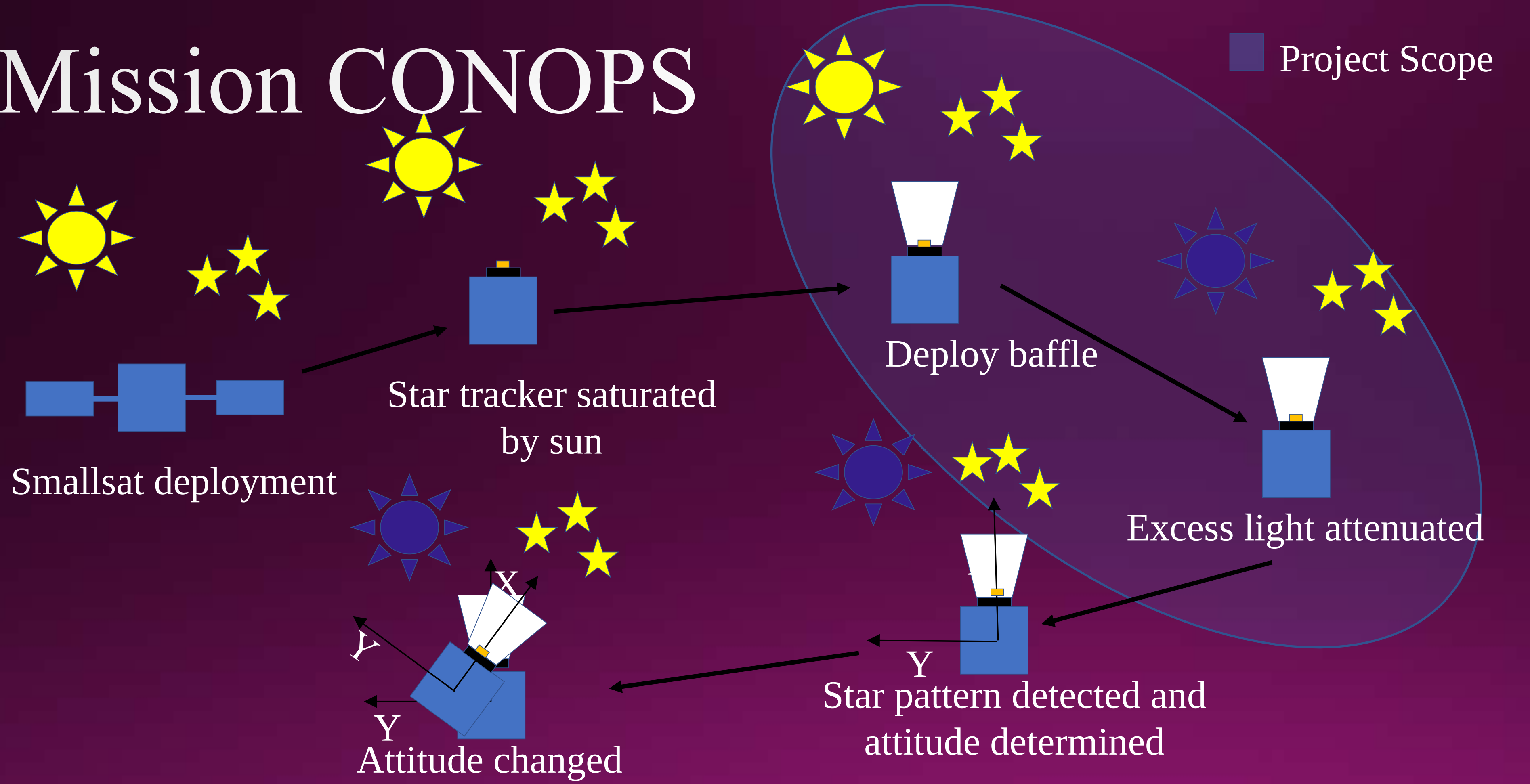
87 mm



Project Goals

- Develop a prototype deployable baffle for a star tracker to be used on a small satellite platform
- Design and manufacture a deployable baffle to limit stray light into an optical sensor
- Develop a test methodology and instrumentation suite to measure performance of the baffle for light attenuation
- Perform the tests for the deployment and light attenuation of the baffle

Mission CONOPS



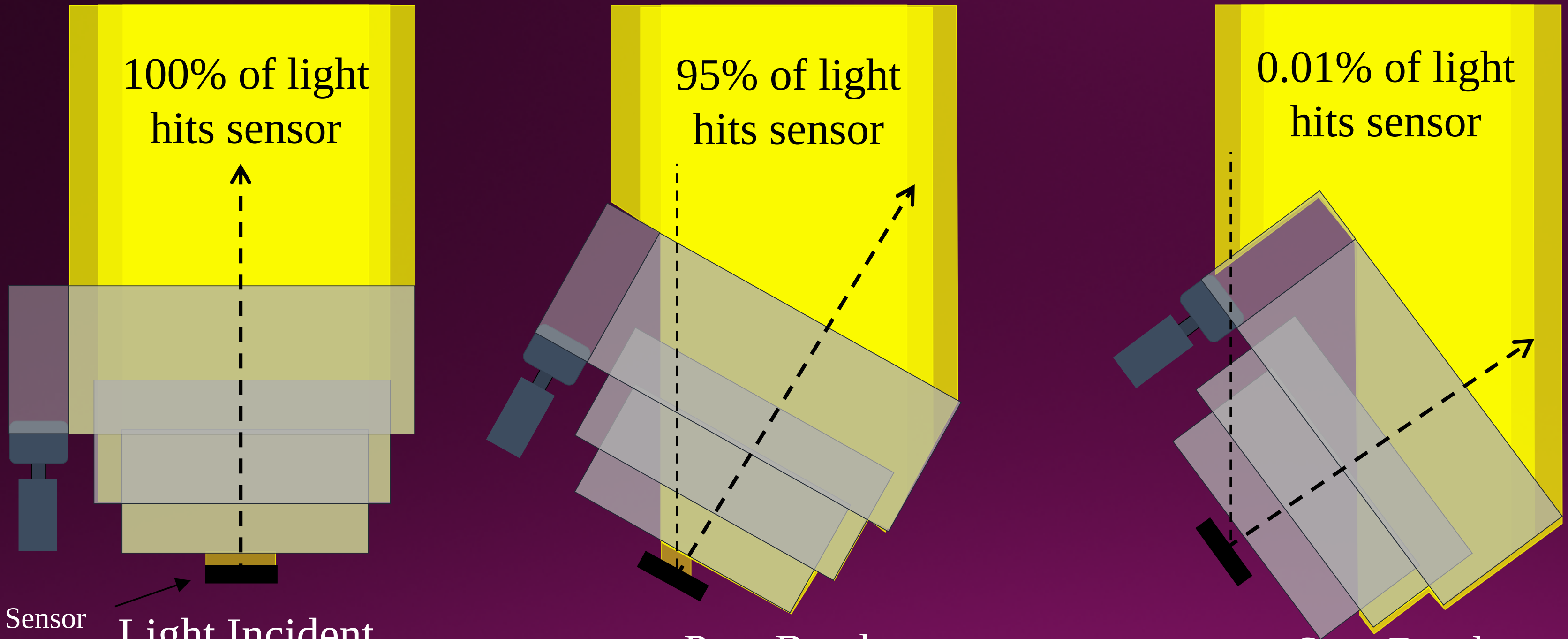
Deployment CONOPS

Stowed Baffle

Power sent to motor

Power screw
rotates and deploys

Light Attenuation CONOPS



Light Incident Angle: 0°

Pass Band Requirement: >10°

Stop Band Requirement: <30°

Requirements

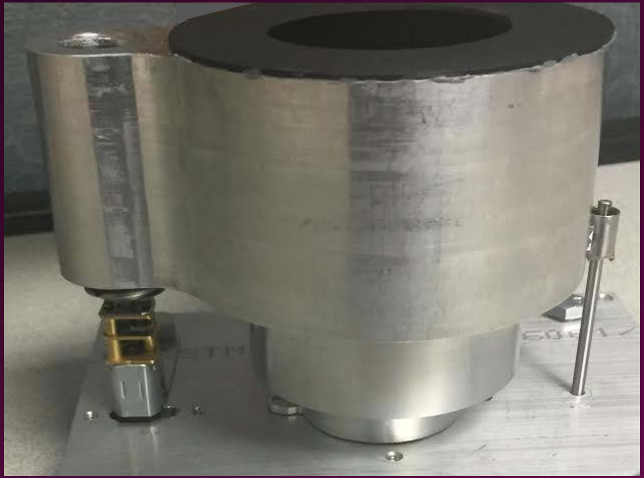
- **FR1: Baffle shall be deployable**
  - DR 1.1: Deployable using 28V
  - DR 1.2: Full deployment ground testing shall be conducted
- **FR2: Baffle shall fit within volume constraints**
  - DR 2.1: Fit within 125x125x50mm box
- **FR3: Baffle shall adhere to mass constraints**
  - DR 3.1: Mass less than 300g
- **FR4: Baffle shall attenuate light**
  - DR 4.1: Ground testing shall be done to determine light obscuration
  - DR 4.2: 99.9% light attenuation at 30^0
  - DR 4.3: Baffle shall have a pre-obscuration angle of $>10^0$

Levels of Success

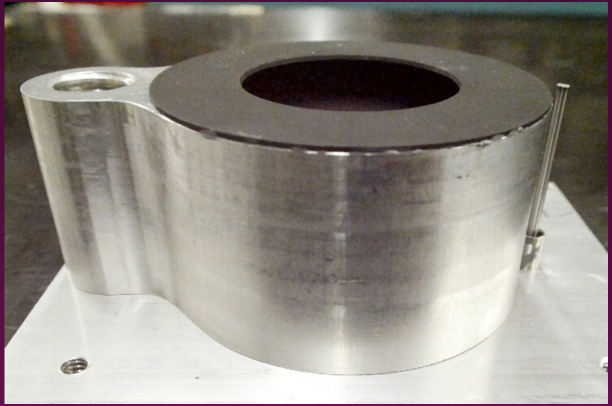
Functional Requirements	Tier 1	Tier 2
FR1: Baffle shall be deployable	Manual deployment	Electronic deployment with wired connection
FR2: Baffle shall conform to stowed volume constraint	175 mm x 175 mm x 50 mm	125 mm x 125 mm x 50 mm
FR3: Baffle shall adhere to mass constraint	< 500 grams	< 300 grams
FR4: Baffle shall attenuate light to 99.9%	At 40° light incidence angle	At 30° light incidence angle

Design Description

Final Product

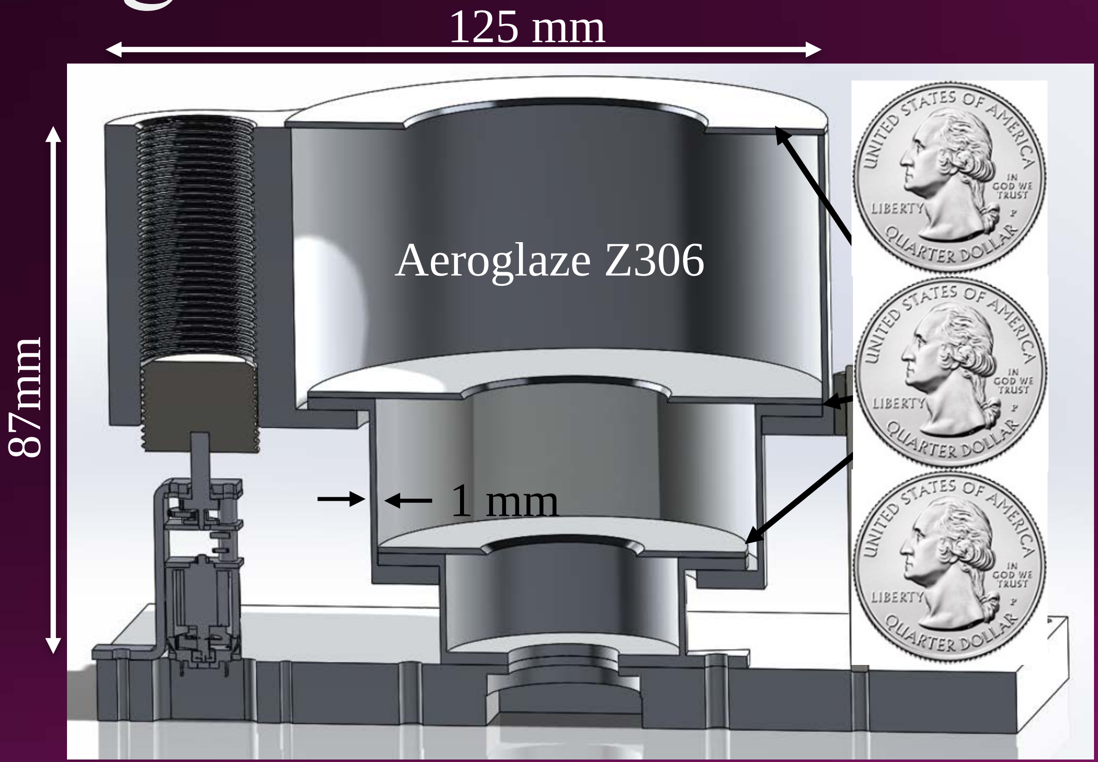


Deployed

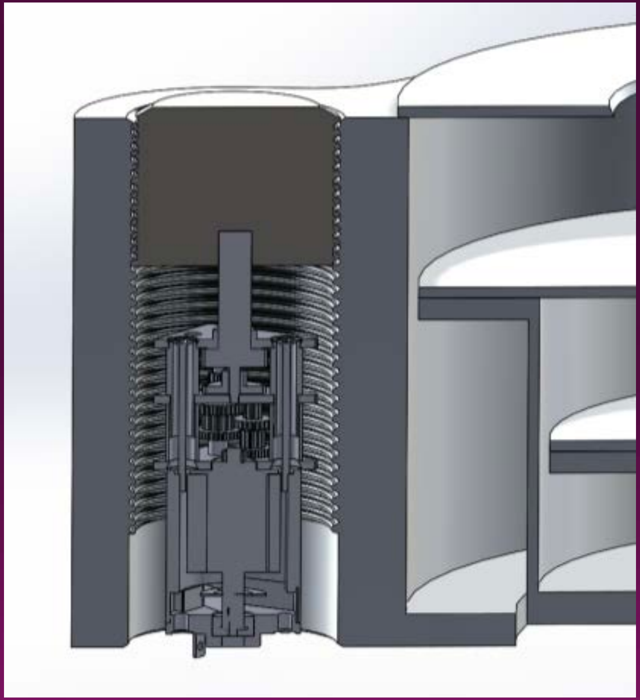


Stowed

Light Attenuation and Deployment



Deployed



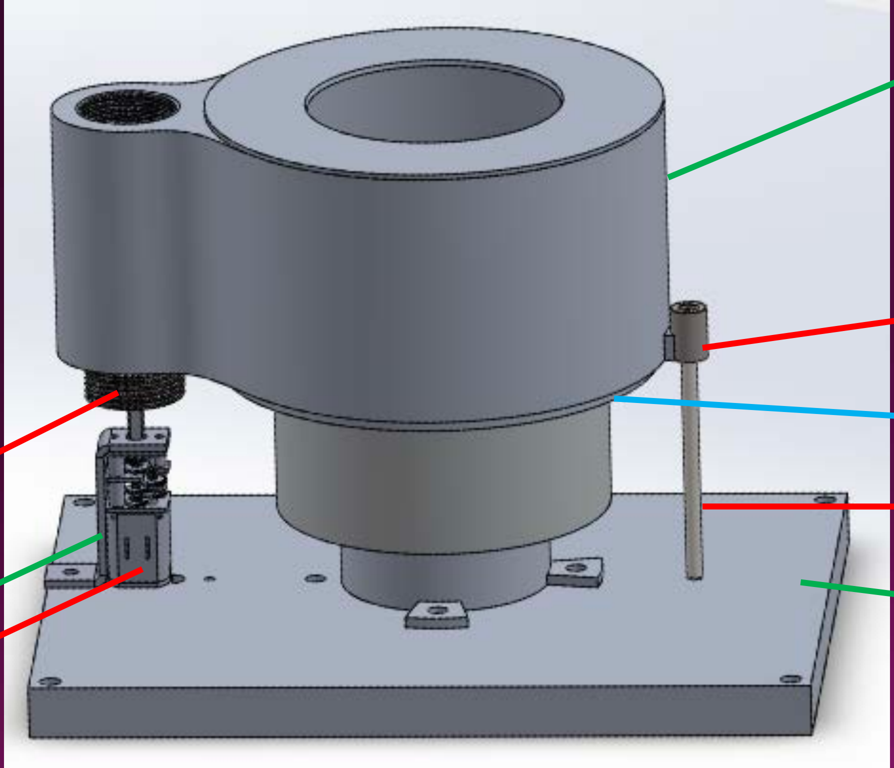
Stowed

Finalized Baffle Design & Manufacturing

COTS

Manufactured in House

Custom Manufactured



Baffle Structure

Linear Bearing

Vanes

Bearing Shaft

Baseplate

Threaded Rod

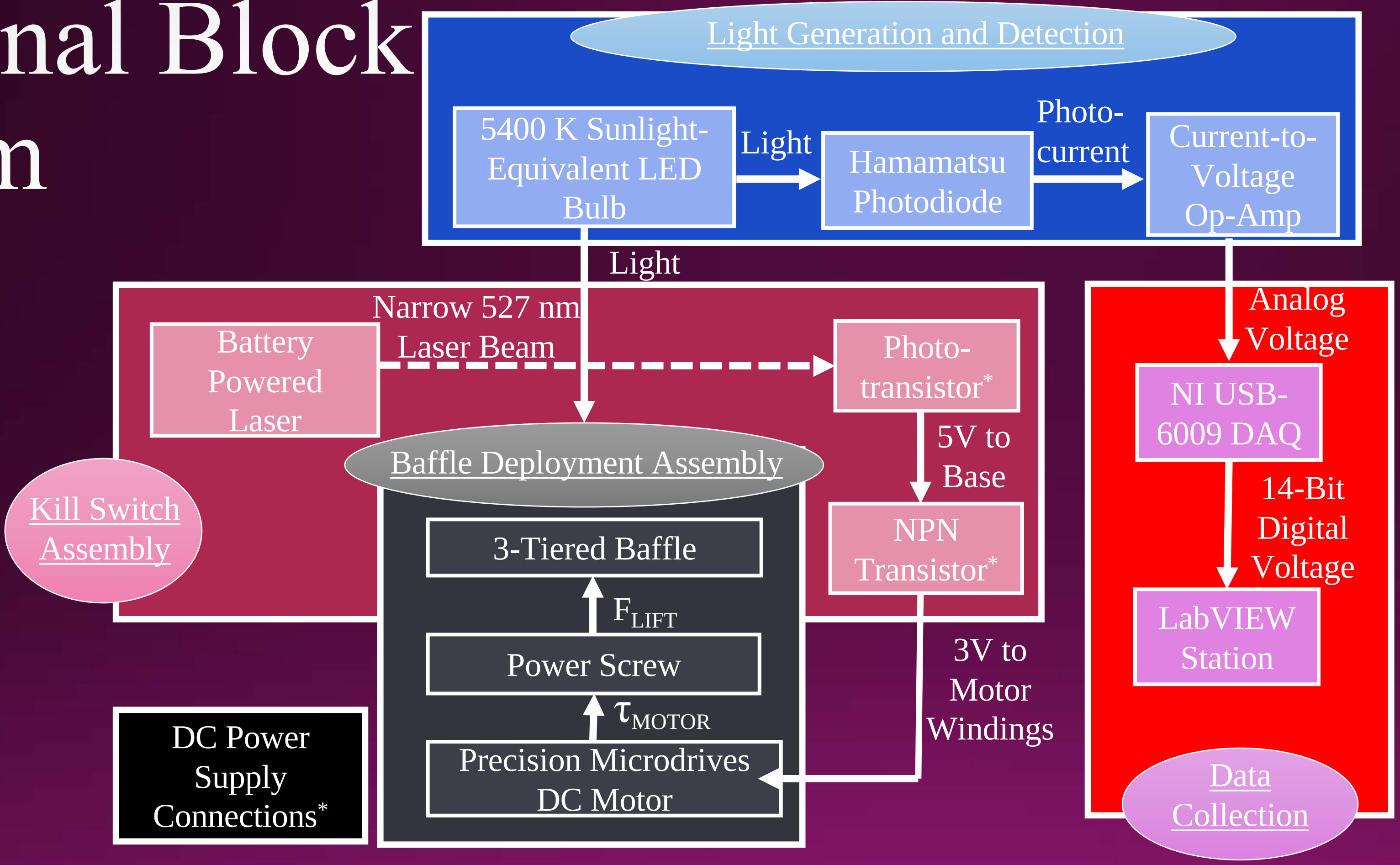
Motor Mount

Motor

Critical Project Elements

CPE	Importance
Deployment (FR1-FR3)	• Cannot attenuate light if not deployed • More efficient stowage
Light Attenuation (FR4)	• Cannot see light from stars if saturated by stray light
Testing (FR1&FR4)	• Verifies and validates properties of the baffle

Functional Block Diagram



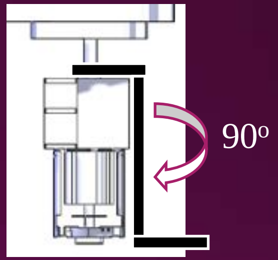
Changes Since TRR

Linear Bearing Adhesive

- Changed from Loctite Liquid Weld to Gorilla Glue
    - Changed due to Loctite curing to a flexible solid

Motor Mount

- Orientation changed due to motor binding issues during deployment testing
    - No net impact on mass or volume constraints



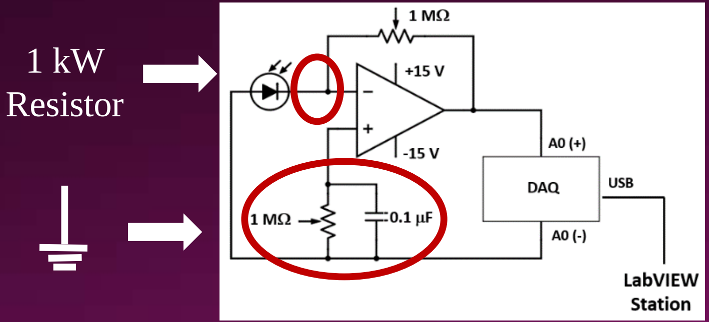
Changes Since TRR

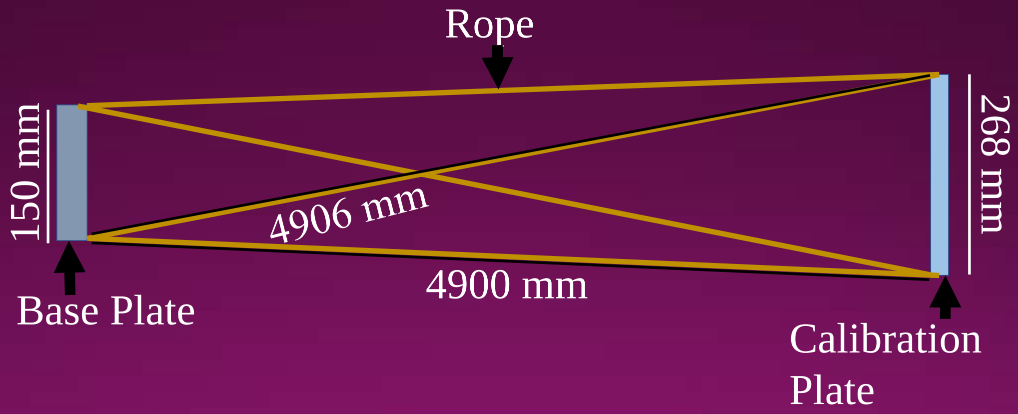
Photo-Amplifier Circuit

- Grounded non-inverting input
  - Proper op-amp functionality
- Added inverting-input resistor
  - Finer amplification control

Testing

- No calibration ropes
  - Tape measure within tolerance
- Laser level instead of laser pointers
  - More accurate





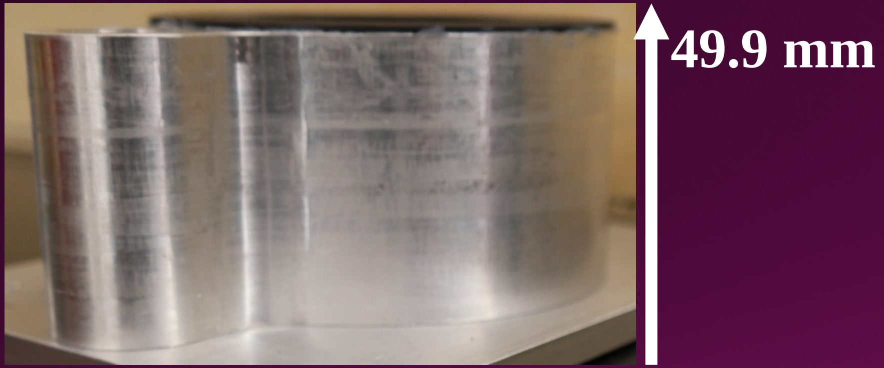
Mass Budget

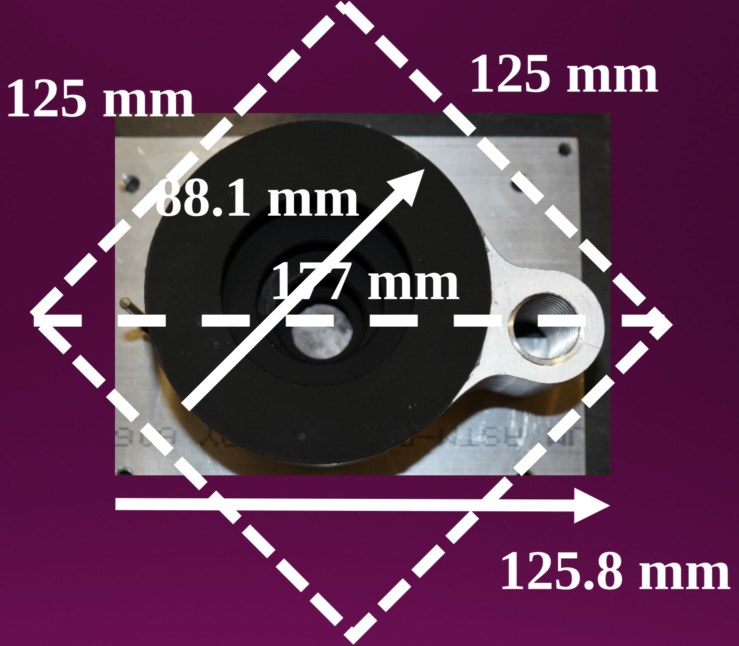
- **FR3: Baffle shall adhere to mass constraints ★**
  - DR 3.1: Mass less than 300g★

Component	CDR Mass with AIAA Standard Percent Mass Growth Allowance (g)	CDR Mass (g)	Measured Mass (g)
Baffle tiers + vanes + bearing + spacer + coating + adhesive	264.5	228.36	220.9
Motor	10.61	10.3	14.5
Linear bearing shaft	2.83	2.75	3.8
Steel screw	21.97	21.33	21.6
Motor mount	3.34	2.9	0.7
Total	303.26	265.64	261.5

Volume Budget

- **FR2: Baffle shall fit within volume constraints** ★
  - DR 2.1: Fit within 125x125x50mm box ★

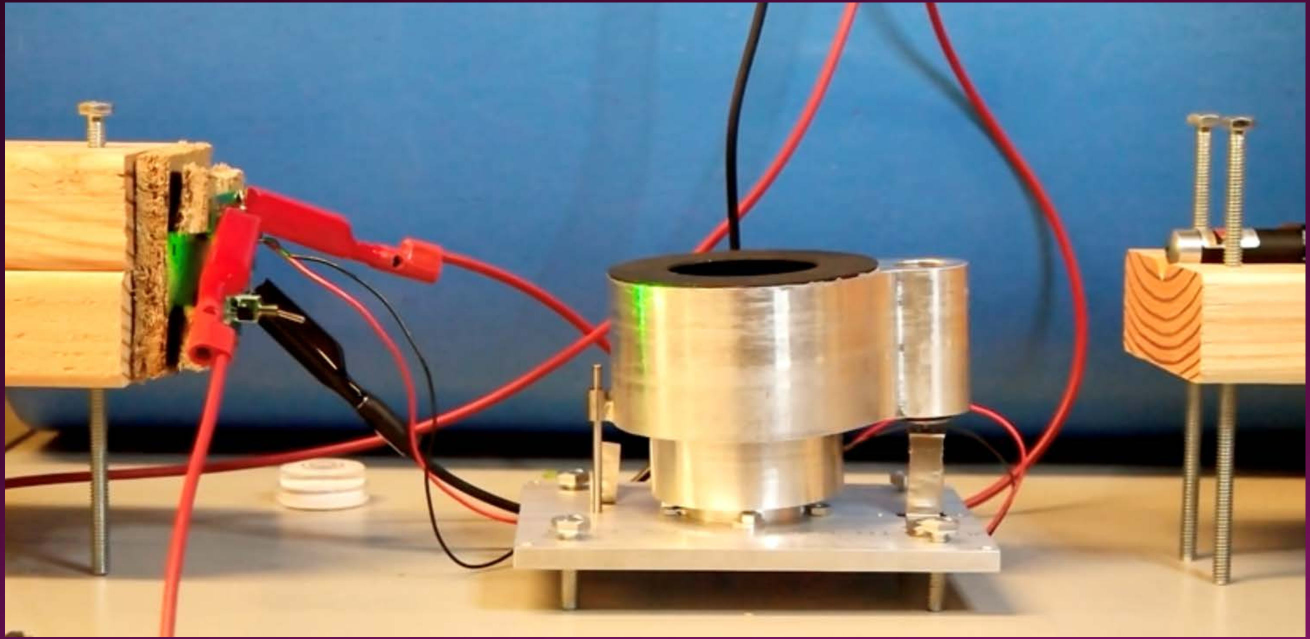




FR2: Stowed Volume	Requirement (mm)	Actual (mm)
Height	50	49.9
Width	125	88.1
Diagonal	177	125.8

Testing Overview & Results

Deployment Testing



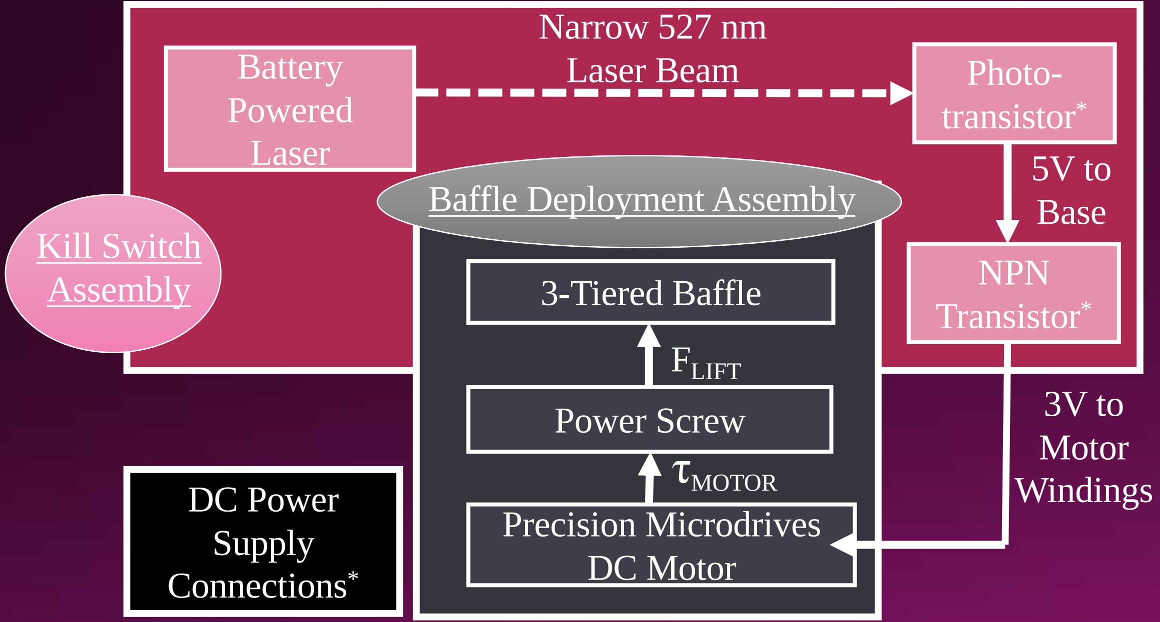
Test Overview - Test Purpose

- Validate customer requirement
- Ensure baffle deploys to necessary height for optical performance (>86mm)
- Ensure baffle doesn't over deploy and damage it (<88mm)

Requirement	Metric
FR1: Baffle shall be deployable	Yes or no
DR1.2: Full deployment ground testing shall be conducted	Test 1: 86 mm Test 2: 88mm

Test Overview - How and Where

How:



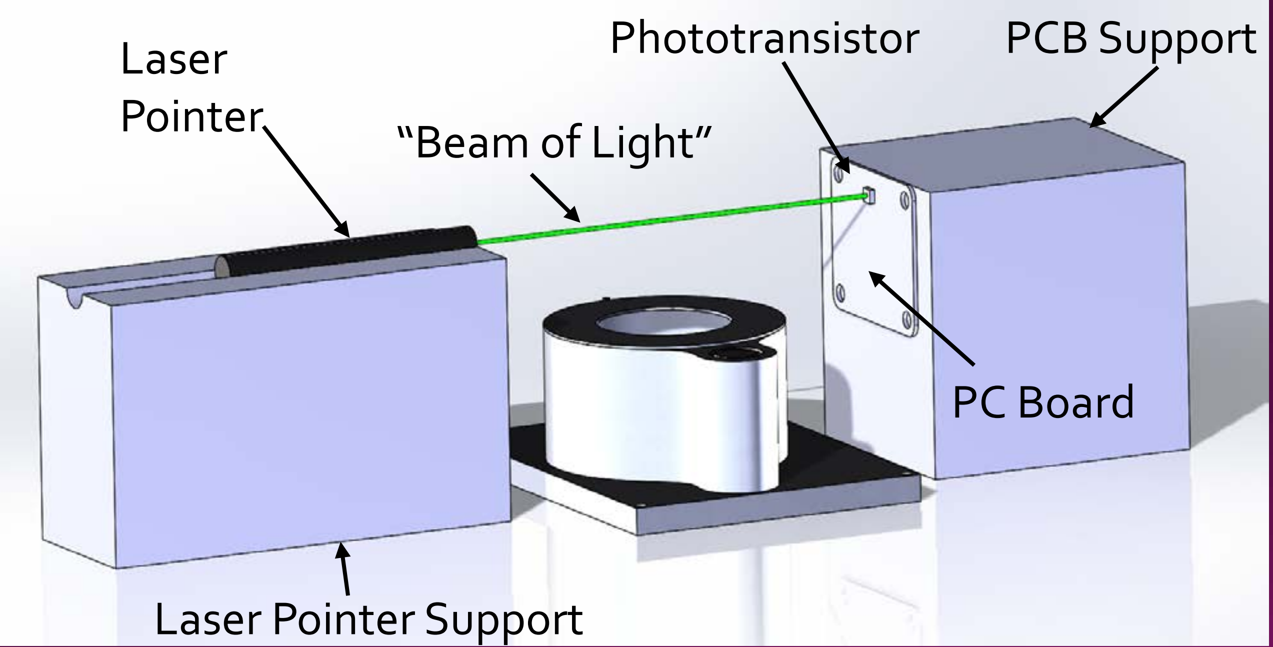
Where:

- Trudy's lab

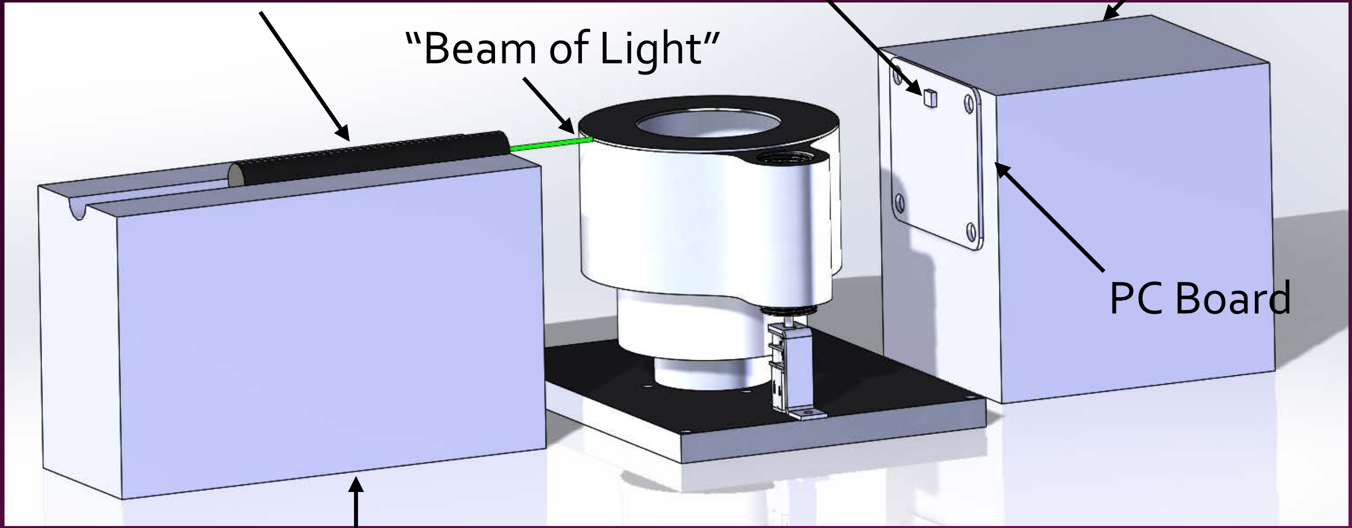
Test Overview - Overview

Test Number	Laser Height	Laser interrupted?	Achieved baffle deployment height	Deployment stop method
1	86 mm	Yes	>86 mm	Phototransistor circuit break
2	88 mm	No	<88 mm	Mechanical thread stop, manual voltage shut off

Test Overview – Details and Fixtures

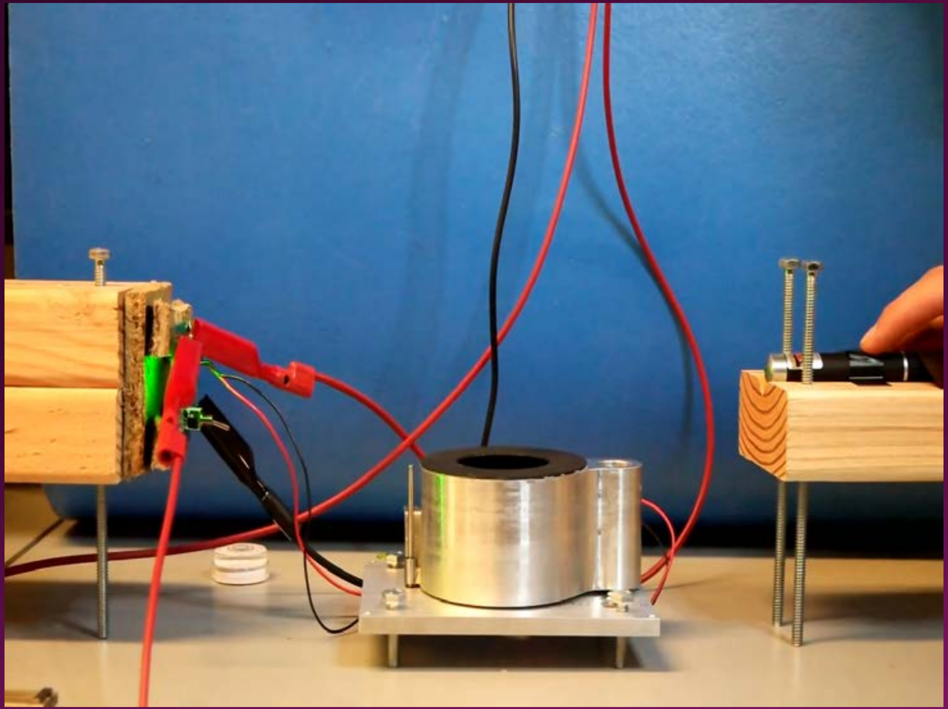


Test Overview – Details and Fixtures



Purpose and Objectives | Design Description | Testing Overview and Results | Systems Engineering | Project Management

Deployment Video

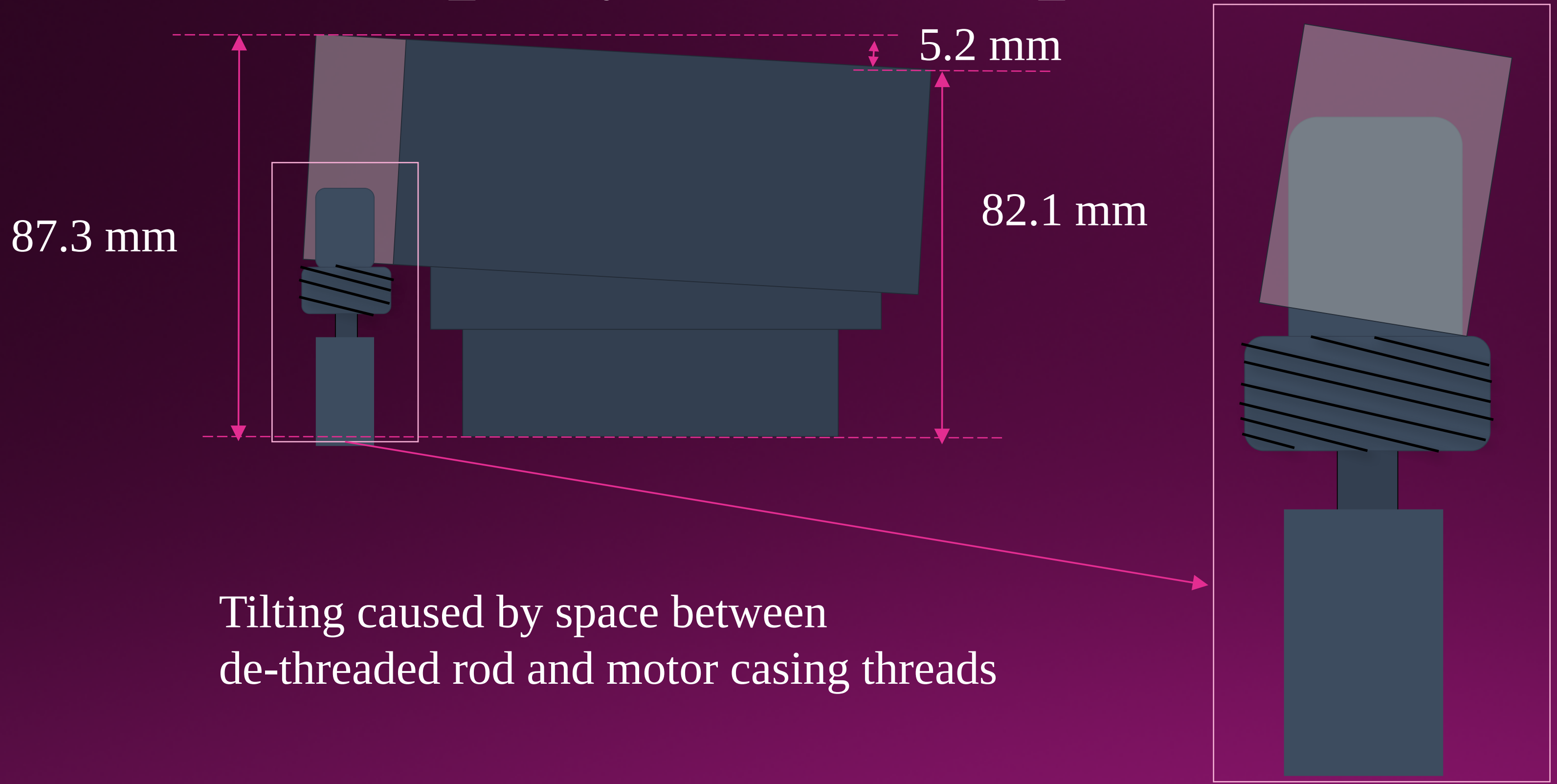


Test Results - Requirement validation

Test	Motor Side Height	Bearing Side Height	Laser Height
1	87.249 mm	82.067 mm	86 mm
2	87.732 mm	81.585 mm	88 mm

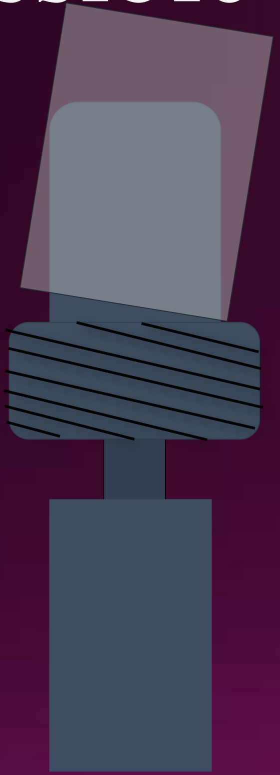
Metric	Requirement Met
FR1: Baffle shall be deployable	Partially Met
DR1.1: Deployable using 28V	Yes ☆
DR1.2: Full deployment ground testing shall be conducted	Yes ☆

Uneven Deployment Explanation

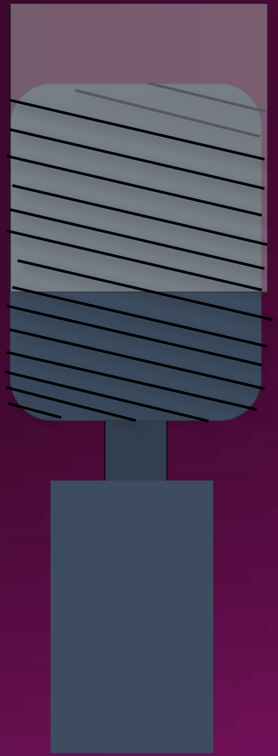


Tilting caused by space between
de-threaded rod and motor casing threads

Possible Solutions



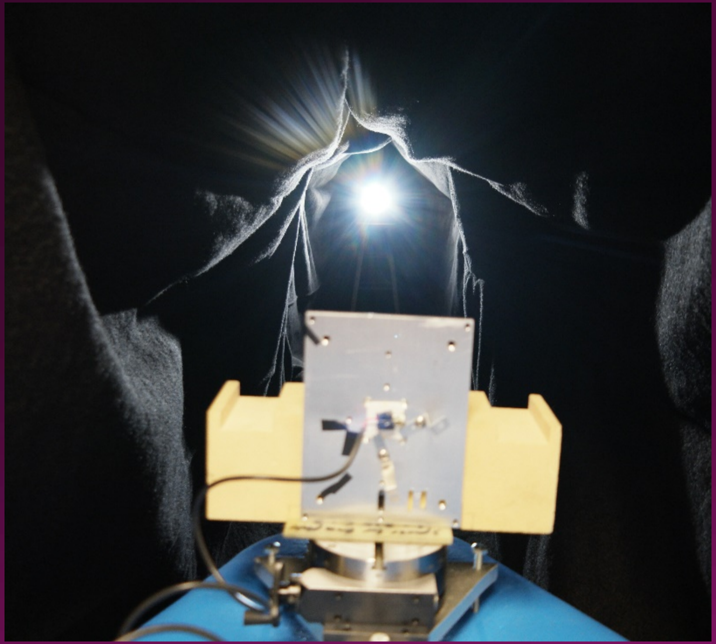
Current Design



Fully Threaded Rod

- Fully threaded rod, takes away tilting
  - No mechanical stop
  - Precise timing for deployment stop
- Increase diameter of de-threaded rod to limit space causing tilt

Light Attenuation



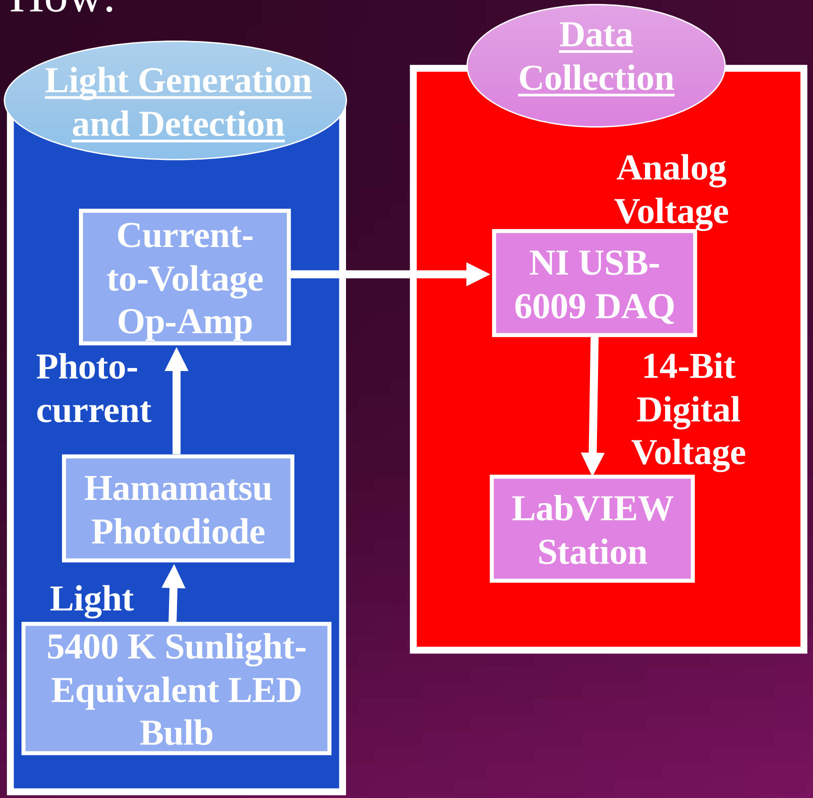
Test Overview - Purpose

- Validate customer requirement
- Designed to simulate dark space and apparent size of the Sun
- Characterize light attenuation properties of the baffle

Requirement	Angle	Incident Relative Power	Percentage of Light Hitting the Sensor
DR4.3: Pass-band	> 10º	0.95	95%
FR4: Stop-band	< 30º	0.0001	0.01%

Test Overview – How and Where

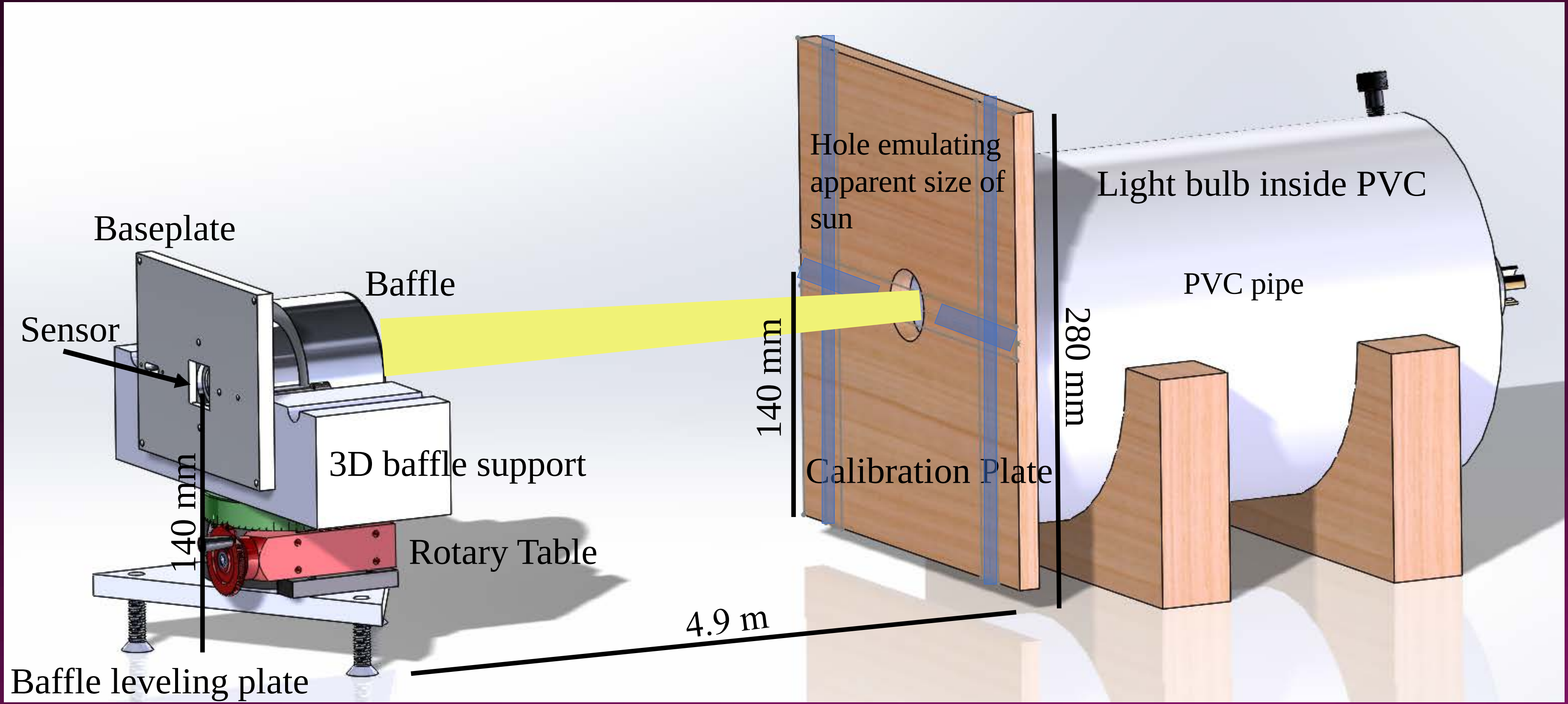
How:



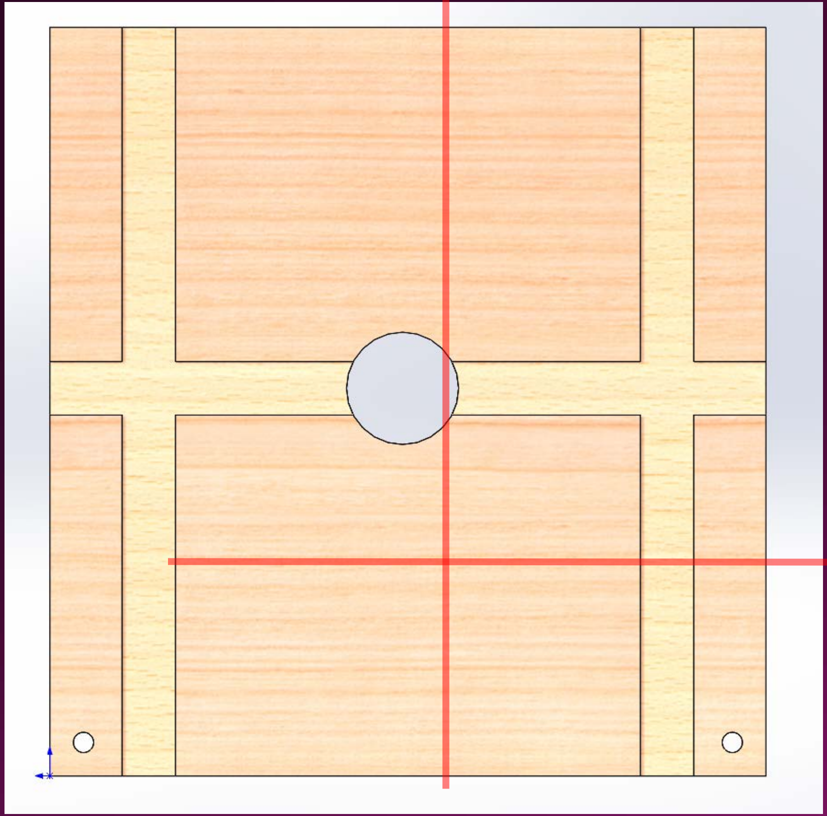
Where:

- CNL clean room
- 19ft felt tunnel

Test Overview – Fixtures



Test Overview - Calibration



- Insert the Laser level into the trough
- Turn on the laser level
- Rotate the baffle/negative/rotary table to line up in longitudinal zones
- Turn laser 90 º
- Turn leveling bolts to line up in the lateral zone

Tolerance:

Distance ± 0.2 m

Changes resulting obscuration angle by 0.40°

Test Overview - Overview

Two different tests:

- Symmetric
- Asymmetric
  - Middle tier offset by 2 mm

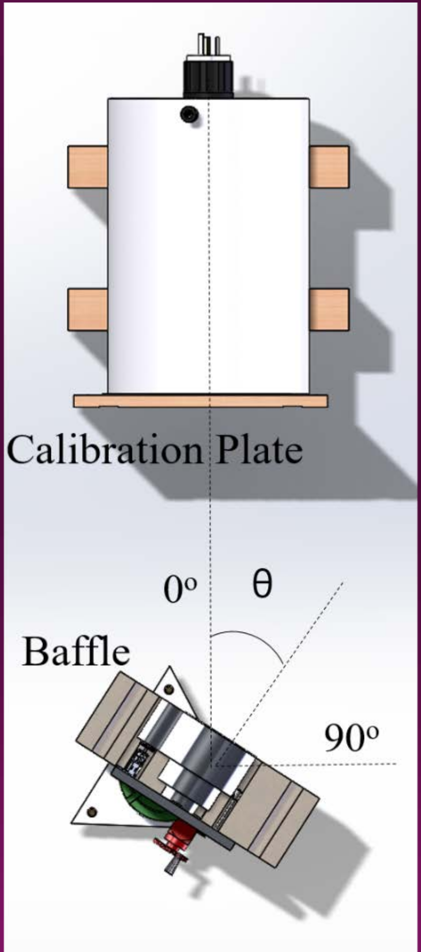
Symmetric Baffle

Asymmetric Baffle

Test Overview - Details

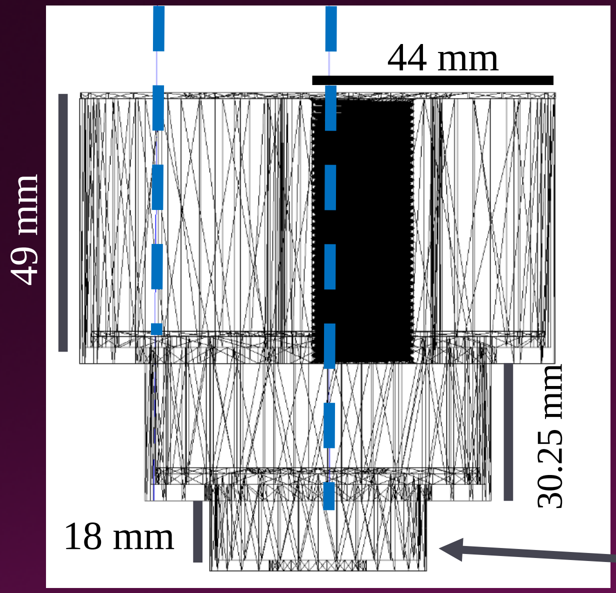
- Take voltage reading at 0^o
- Take voltage readings from -30^o to 30^o by 4^o incriments
  - Increase resolution to 0.1^o as needed
- Calculate power from known resistance and measured voltages
- Calculate relative power at all angles

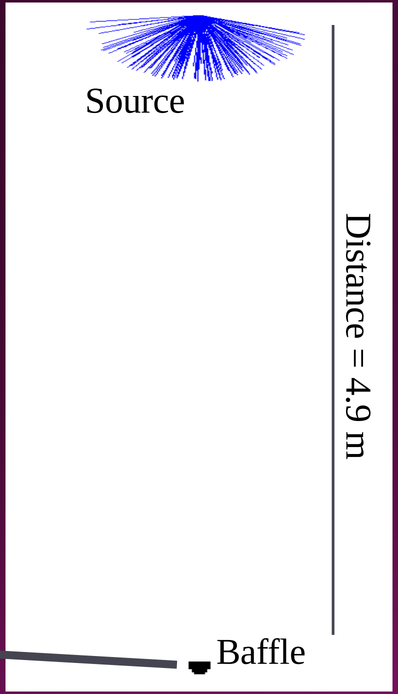
$$P_{rel} = \frac{P}{P_0}$$



Model vs Test

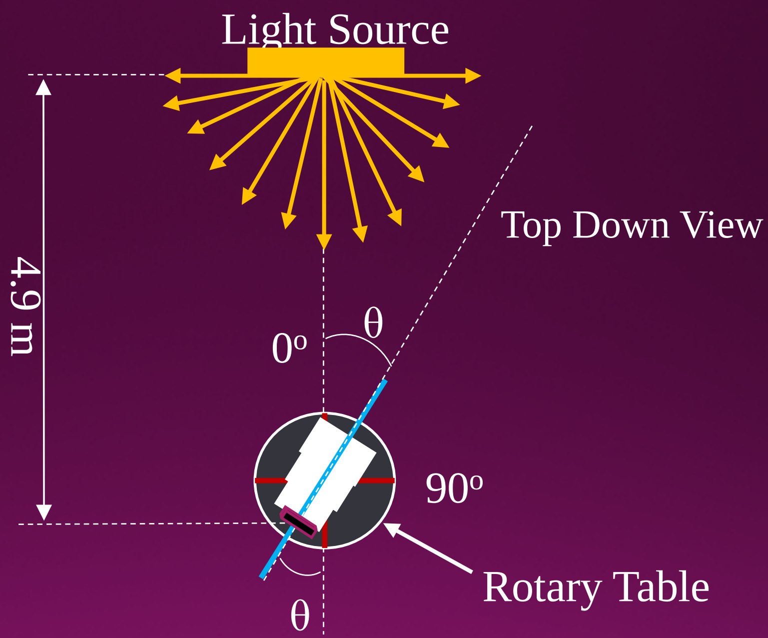
Zemax Ray Tracing Model



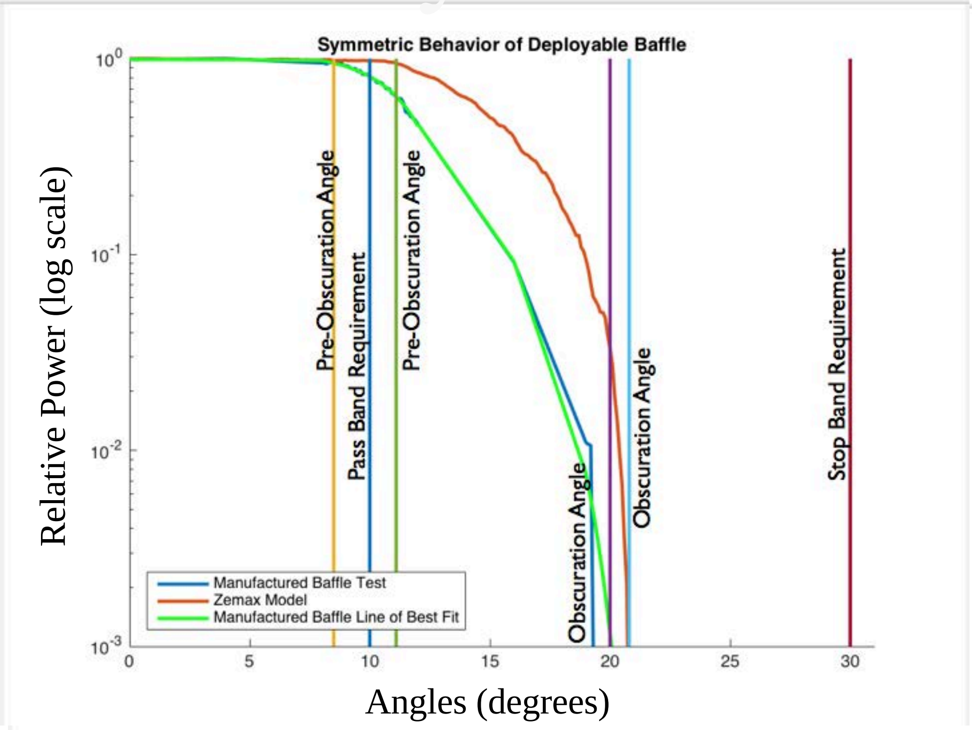


Optical Ray Tracing layout

Actual Test Setup



Test Results – Symmetric Test



<u>Requirements</u>

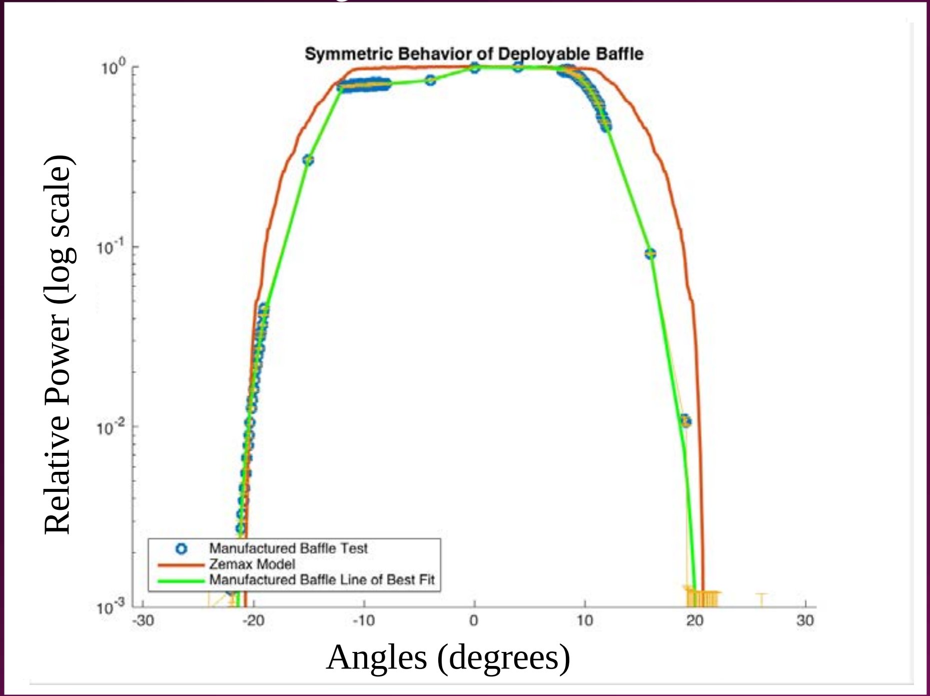
Pass Band: Angle > 10°

Stop Band: Angle < 30°

Testing Range	Pre-Obscuration - Model	Pre-Obscuration	Obscuration - Model	Obscuration
0° < θ < 30°	11.1°	8.5° ± 0.4°	20.8°	20.0° ± 0.4°

Purpose and Objectives | Design Description | Testing Overview and Results | Systems Engineering | Project Management

Test Results – Symmetric Test



Recommendations

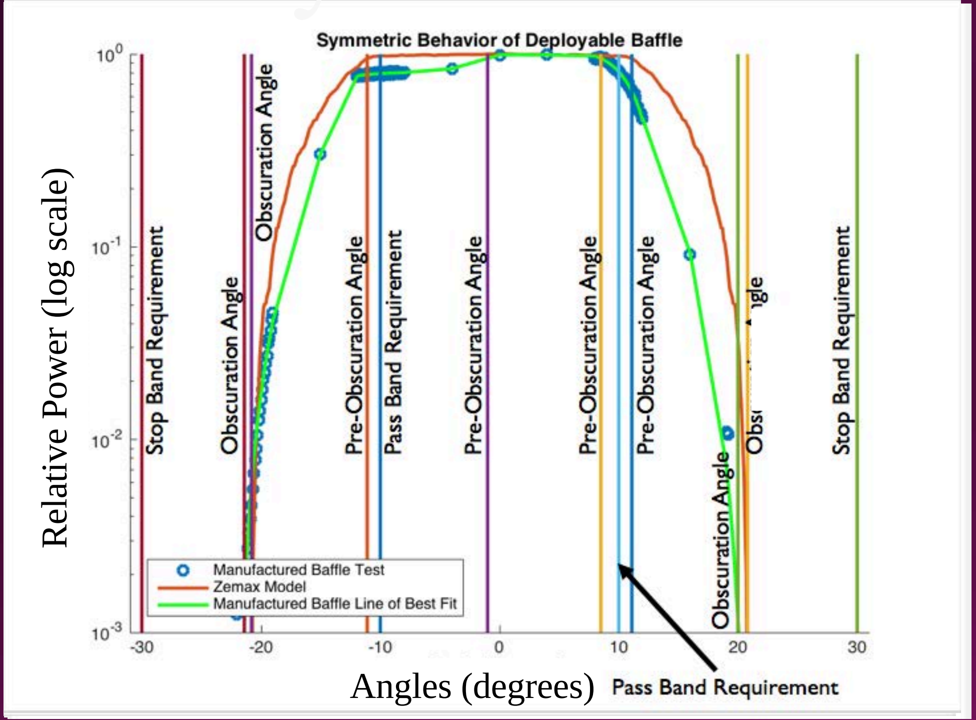
- Examine thermal contributions of electronic components
- Time investigation for repeated test

Requirements

Pass Band: Angle > 10°
Stop Band: Angle < 30°

Testing Range	Pre-Obscuration - Model	Pre-Obscuration	Obscuration - Model	Obscuration
0° < θ < 30°	11.1°	8.5° ± 0.4°	20.8°	20.0° ± 0.4°
-30° < θ < 0°	-11.1°	-1.0± 0.4°°	-20.8°	-21.4° ± 0.4°

Test Results – Symmetric Test



Recommendations

- Examine thermal contributions of electronic components
- Time investigation for repeated test

<u>Requirements</u>

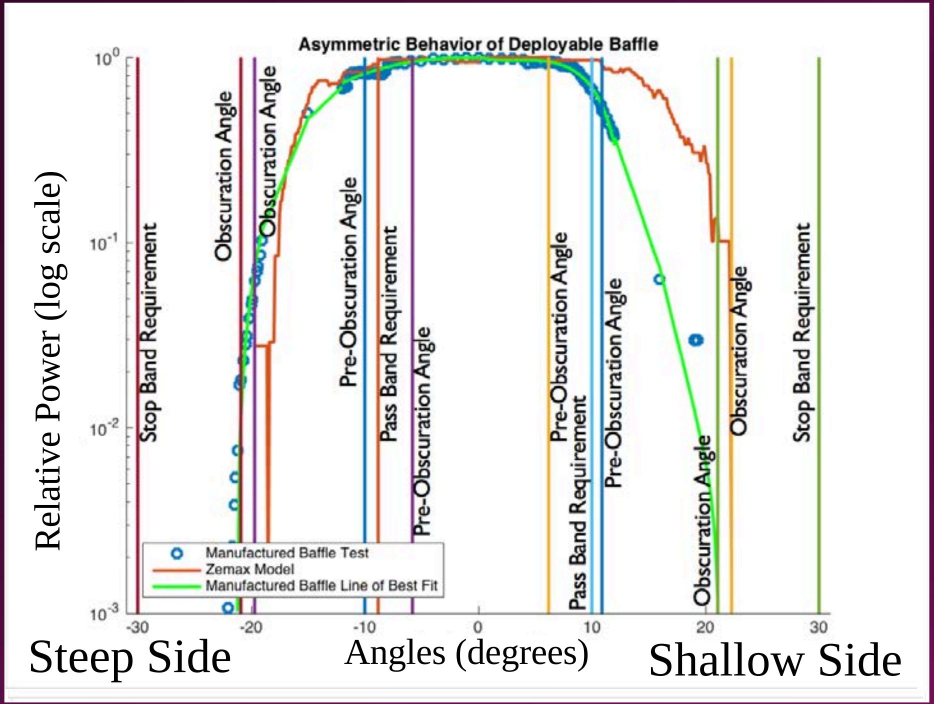
Pass Band: Angle > 10°

Stop Band: Angle < 30°

Testing Range	Pre-Obscuration - Model	Pre-Obscuration	Obscuration - Model	Obscuration
0° < θ < 30°	11.1°	8.5° ± 0.4°	20.8°	20.0° ± 0.4°
-30° < θ < 0°	-11.1°	-1.0± 0.4°°	-20.8°	-21.4° ± 0.4°

Test Results – Asymmetric Test

- Experimental results deviated from Zemax model
  - Real world testing versus simulation
- Recommendations
  - More precise coating application
  - Placement of photodiode



<u>Requirements</u>

Pass Band: Angle > 10°

Stop Band: Angle < 30°

Testing Range	Pre-Obscuration - Model	Pre-Obscuration	Obscuration - Model	Obscuration
0° < θ < 30°	10.9°	6.2° ± 0.4°	22.3°	21.1° ± 0.4°
-30° < θ < 0°	-8.8°	-5.8° ± 0.4°	-19.7°	-20.9° ± 0.4°

Test Results – Data Summary

Negative	Test Range	Pre-Obscuration - Model	Pre-Obscuration	Obscuration - Model	Obscuration
A	$0° < \theta < 30°$	11.1°	-8.7° ± 0.4°	20.8°	20.0° ± 0.4° *
A	$-30° < \theta < 0°$	-11.1°	-7.5° ± 0.4°	-20.8°	-20.7° ± 0.4° *
B	$0° < \theta < 30°$	10.9°	6.2° ± 0.4°	22.3°	21.1° ± 0.4°
B	$-30° < \theta < 0°$	-8.8°	-5.8° ± 0.4°	-19.7°	-20.9° ± 0.4°
C	$0° < \theta < 30°$	11.1°	8.5° ± 0.4°	20.8°	22.3° ± 0.4°
C	$-30° < \theta < 0°$	-11.1°	-1.0° ± 0.4°	-20.8°	-19.7° ± 0.4°
D	$0° < \theta < 30°$	10.9°	8.9° ± 0.4°	22.3°	21.0° ± 0.4° *
D	$-30° < \theta < 0°$	-8.8°	-1.2° ± 0.4°	-19.7°	-21.3° ± 0.4°

Over All Baffle Behavior		
Pre-Obscuration Angle	$\|-1.0°\| \leq \theta \leq \|8.9°\|$	🚫
Obscuration Angle	$\|-19.7°\| \leq \theta \leq \|22.3°\|$	☆

Legend
Symmetric Baffle
Asymmetric Baffle

* = Never Reached Stop Band

Test Results - Requirement Validation

Metric	Requirement Met
FR4: Baffle shall attenuate light	Partially Met
DR4.1: Ground testing shall be done to determine light obscuration	Yes ☆
DR4.2: 99.9% light attenuation at 30°	Yes ☆
DR4.3: Baffle shall have a Pre-Obscuration angle of >10^0	No ⦸

Requirement Validation

FR1 – Explanation

Functional Requirements	Tier 1	Tier 2
FR1: Baffle shall be deployable	Manual deployment	Electronic deployment with wired connection

- DR1.1: Deployable using 28V ★
- DR1.2: Full deployment ground testing shall be conducted ★

FR2 – Explanation

Functional Requirements	Tier 1	Tier 2
FR2: Baffle shall conform to stowed volume constraint	175 mm x 175 mm x 50 mm	125 mm x 125 mm x 50 mm

- DR 2.1: Fit within 125x125x50 mm box ★

FR3 – Explanation

Functional Requirements	Tier 1	Tier 2
FR3: Baffle shall adhere to mass constraint	< 500 grams	< 300 grams

- DR 3.1: Weight less than 300g ★

FR4 – Explanation

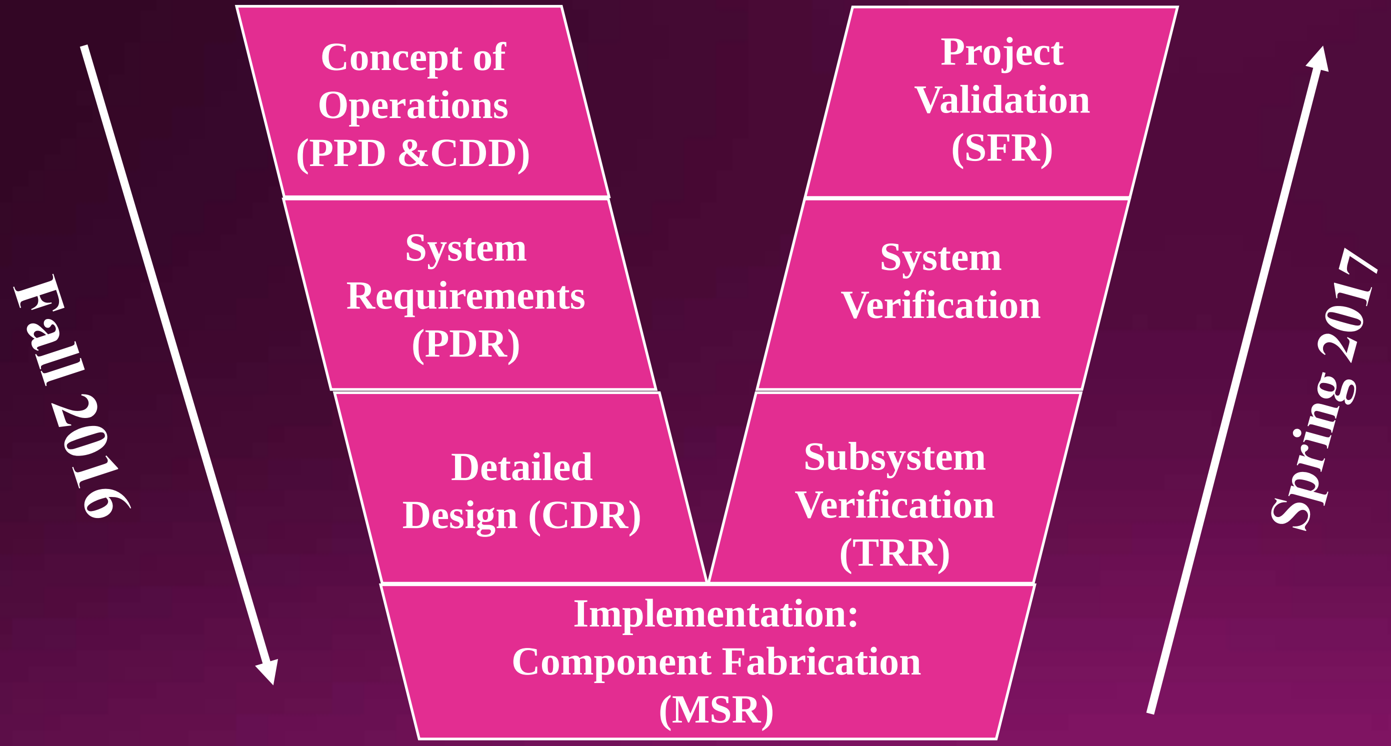
Functional Requirements	Tier 1	Tier 2
FR4: Baffle shall attenuate light to 99.9%	At 40° light incidence angle	At 30° light incidence angle

- DR 4.1: Ground testing shall be done to determine light obscuration
- DR 4.2: 99.9% light attenuation at 30 degrees
- DR 4.3: Baffle shall have a Pre-Obscuration angle of >10^0

Systems Engineering

Purpose and Objectives | Design Description | Testing Overview and Results | Systems Engineering | Project Management

Systems Engineering Approach



Design Trades

- High Level
  - Deployment method, material selection
    - Mass driven
- Detailed trades
  - Sensor selection, light source, testing location
    - Budget, baffle, environment driven

Key Takeaways

1. **Mass is most constraining factor**
2. **Light sources generate heat, account for it early**

Flow Down

- Deployment method → Motor driven deployment → Linear bearing

- Baffle geometry → Aperture size → Sensor selection
  - Star tracker trait→ 10° field of view → 10° pass-band requirement
  - Sensor selection → Clean room, no diffusing glass

- Test methodology → Dark room
  - Dark room → Clean room → Felt tunnel

Risks from CDR

Red	Unacceptable
Yellow	Acceptable with mitigation
Green	Acceptable

Severity → Likelihood ↓	1	2	3	4	5
5 (Very High)					
4	Baffle deflection		Using dark room		Exceeding radial force limit
3	Exposure to bright light			Exposure to Aeroglaze, shop availability	
2				Inaccurate machining	
1 (Very Low)	Exceeding budget limitations				

Relevant Risks

Red	Unacceptable
Yellow	Acceptable with mitigation
Green	Acceptable

Severity → Likelihood ↓	1	2	3	4	5
5 (Very High)					
4			Using dark room		
3	Baffle deflection			Shop availability	
2			Inaccurate machining		
1 (Very Low)				Exceeding radial force limit	

Risk Results

Risk	Mitigation	Result
RP1: Baffle deflection	Linear bearing, motor mount piece re-design, more secure motor hold and no binding	Tilt during deployment, MATLAB model predicts adding 0.5° to pre-obscuration and 1° to obscuration
RP2: Shop availability	New shop staff member hired, early morning start times, sent vanes out of house	Three week schedule slip, used testing and manufacturing margin, on time project completion
RP3: Exceeding radial force limit	Motor testing of radial loading, careful handling of motor	Successful deployment testing, no motor jam
RP4: Using dark room	Left lights on except during testing, visually marked fishing line, minimized movement during tests	Successful light attenuation testing with no accidents
RP5: Inaccurate machining	Remade top piece, step measuring	Baffle components, sensor and filter fit properly

Challenges

Successes:

- Baffle component integration successful
- Test bed integration successful
  - Electronics and structures

Difficulties:

- Optical knowledge required for project
- Manufacturing issues
  - Shop availability, difficulty/ complexity of pieces
- Technical knowledge distribution
  - Subsystem teams became highly technical early on
  - Difficult to redistribute team resources

Lessons Learned

- Electronics testing early was key to project success
- Writing requirements that encompass all facets is difficult
- Everyone should be involved in manufacturing and testing
  - Understanding complexity, necessary for integration expectations
  - Spread out work to alleviate burden on one person for entire subsystem
- Develop test bed design early on
  - Constant changes caused many iterations and unnecessary/ repetitive work
- Design with end game in mind
  - Design for cure, not symptoms: Fixing only one thing at a time just makes more problems

Project Management

Project Management Approach

- Weekly planning
  - Weekly calls with systems lead
    - Plan Monday meetings and the upcoming weeks
  - Weekly calls with systems lead and advisor
    - Update on team's progress and schedule
    - Get feedback

- Plan out assignments and break up amongst team
  - Assigning internal deadlines

Successes and Difficulties

Successes:

- Highest levels of success strived for and achieved
- Stayed under budget
- Resource utilization
  - Maaco, UCAR/NCAR, CNL
- Time vs money tradeoff

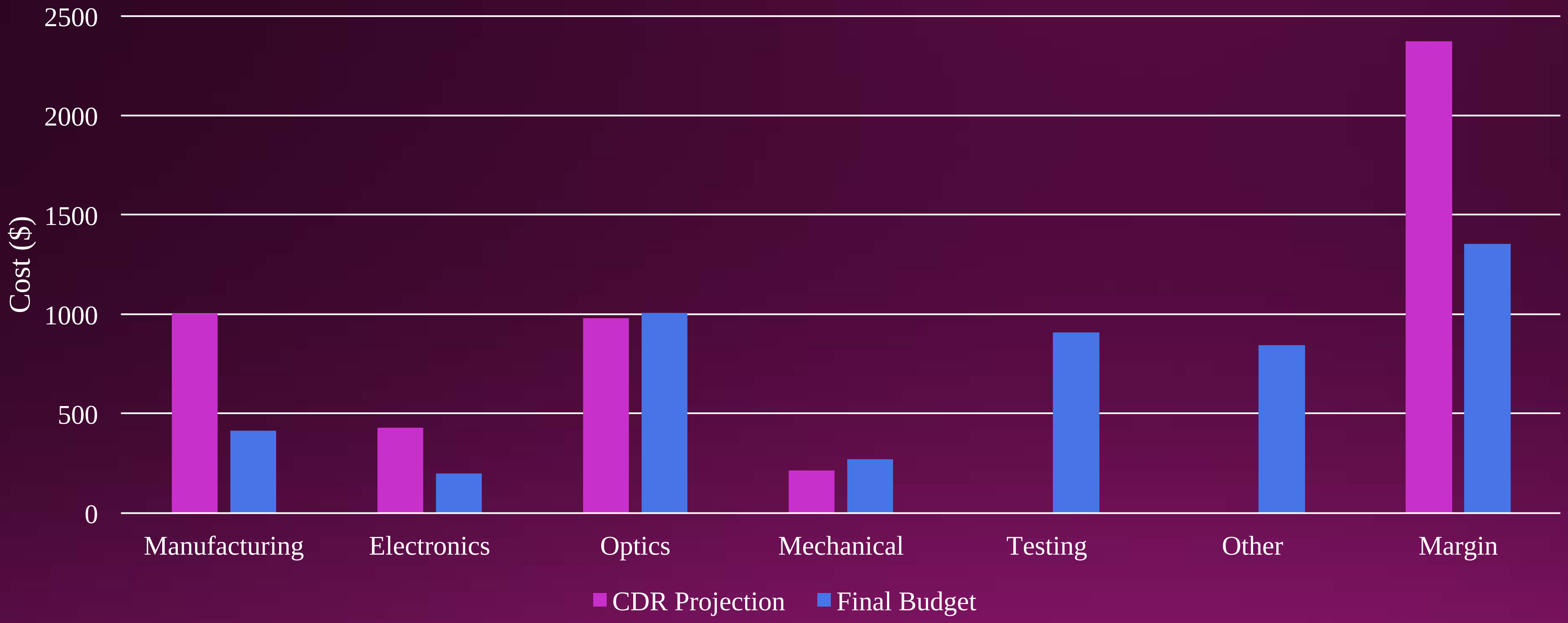
Difficulties:

- Communication
- Keeping progress high when project is at a low
- Schedule slip

Lessons Learned

- Schedule more than enough time then add more margin, early estimates are never accurate
  - 2, π, 5 rule
- Using budget margin to aid schedule
- Have backup plans in place for everything
  - The smallest pieces can take forever to manufacture
- Deadlines come fast no matter how far out you plan
- Communication can always be worked on

Budget Comparison



Industry Cost

Item	Hours	Rate	Total
Work Hours	4272.2	$31.25 per hour	$133,506.25
Overhead Cost		200%	$267,013.50
Project Supplies		$5000	$5000
Clean Room Access	31	$54 per hour	$1674
Standard Zemax Subscription		$4900	$4900
Total			$412,093.75

Special Thanks

- Surrey Satellite Technology U.S.
    - Scott Taylor
- Project Advisor
    - Josh Stamps
- Senior Design Professor
    - Dr. Nabity
- Maaco
- UCAR/NCAR High Altitude Observatory
    - Scott Sewell
    - Phil Oakley
- CNL

Questions?

Sources

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[4] Marciniak, M., Enright, J., Sinclair, D., Dzanba, T., "Microsatellite Star Tracker Baffles: Validation an Testing," AIAA/USU, [https:digital.library.ryerson.ca/islandora/object/RULA%3A3384. Accessed on 7 Mar 2017]

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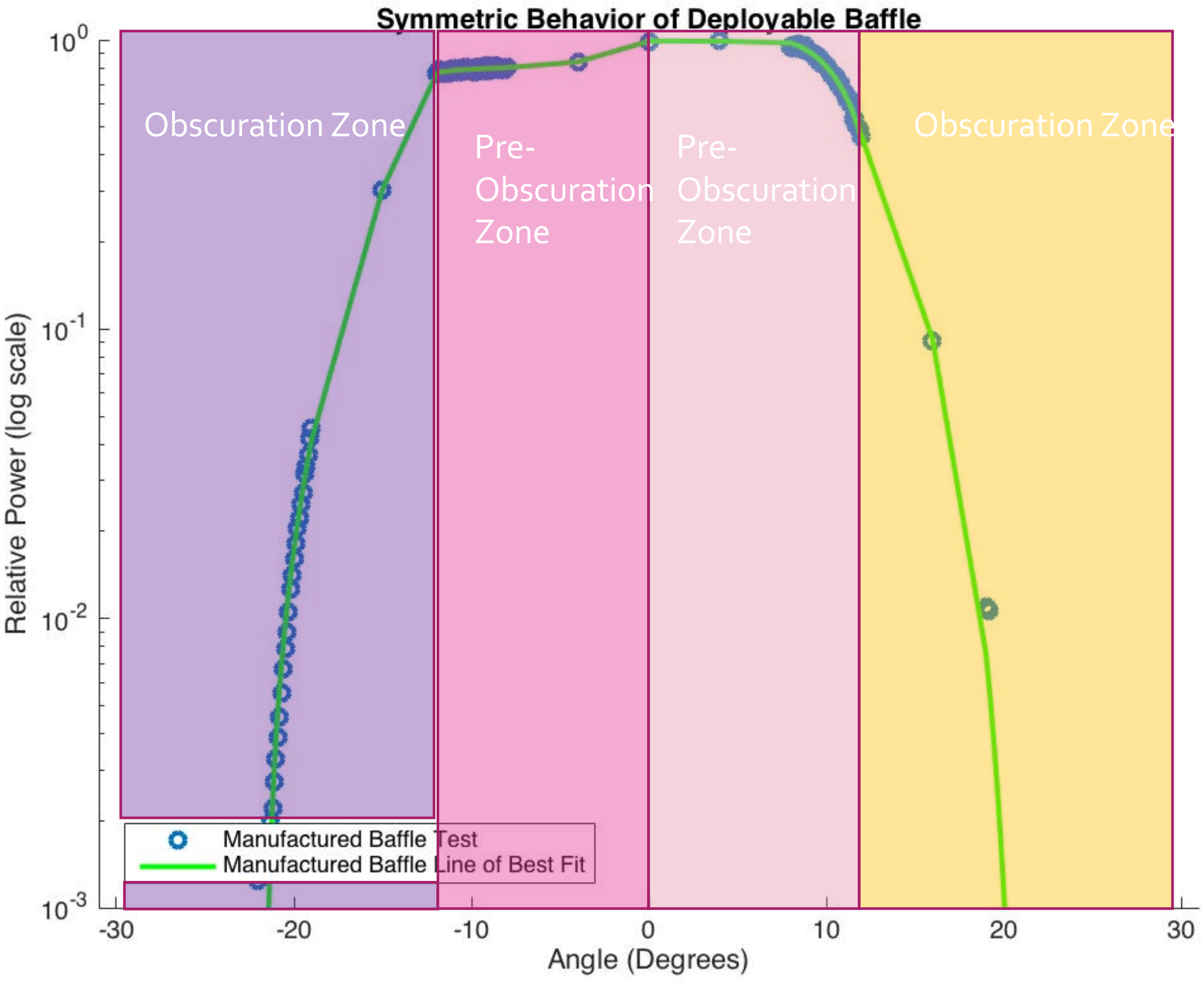
Backup Slides

Budget Numbers

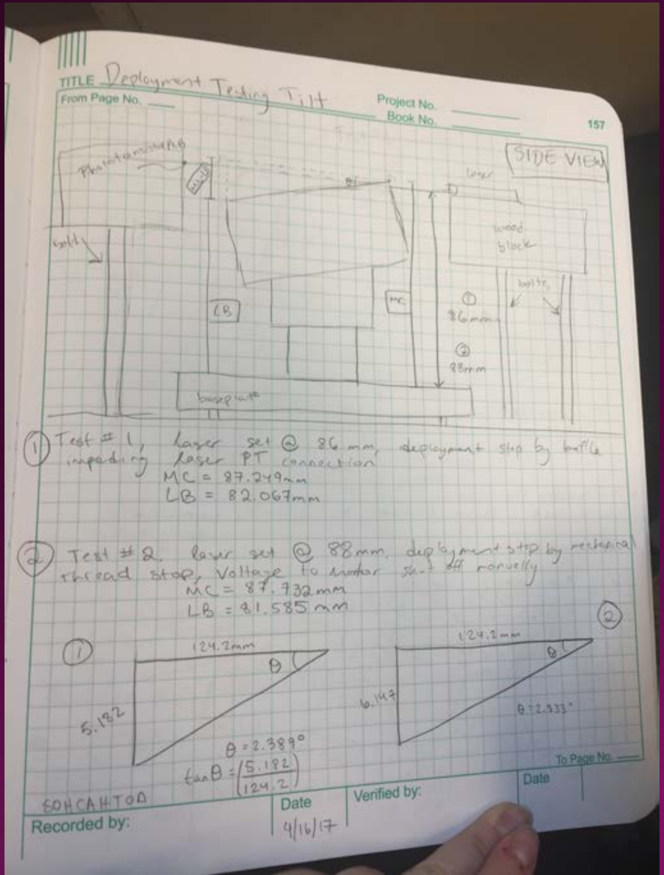
	CDR Projection	Final Budget	Difference
Manufacturing	1002	413.3	588.7
Electronics	430	200.53	229.47
Optics	982	1006.94	-24.94
Mechanical	213	269.32	-56.32
Testing	0	910.31	-910.31
Other	0	844.66	-844.66
Margin	2373	1354.94	1018.06
	5000	5000	0

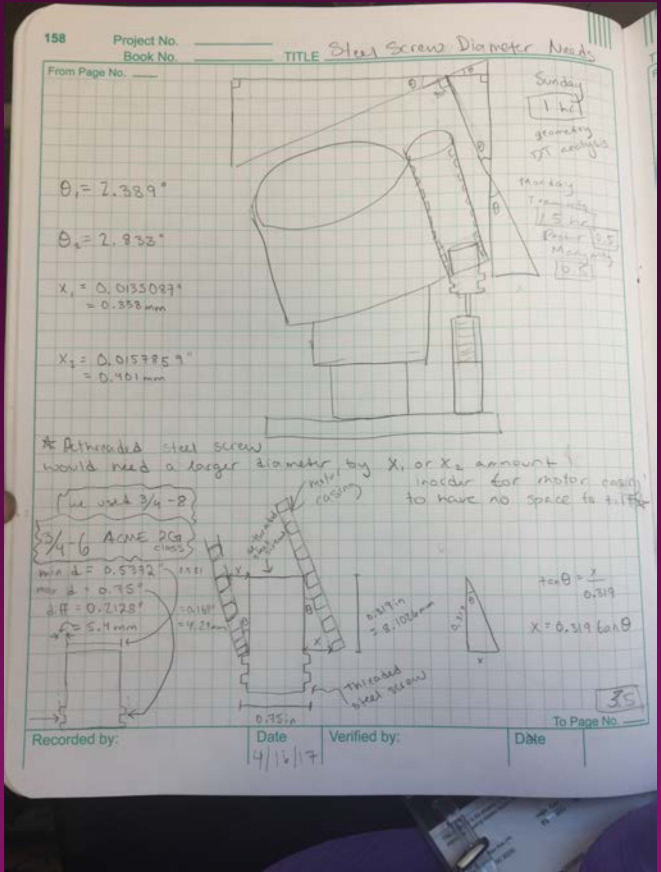


Symmetric Behavior of Deployable Baffle
Relative Power (log scale)
Angle (Degrees)
Obscuration Zone
Pre-Obscuration Zone
Pre-Obscuration Zone
Obscuration Zone
Manufactured Baffle Test
Manufactured Baffle Line of Best Fit

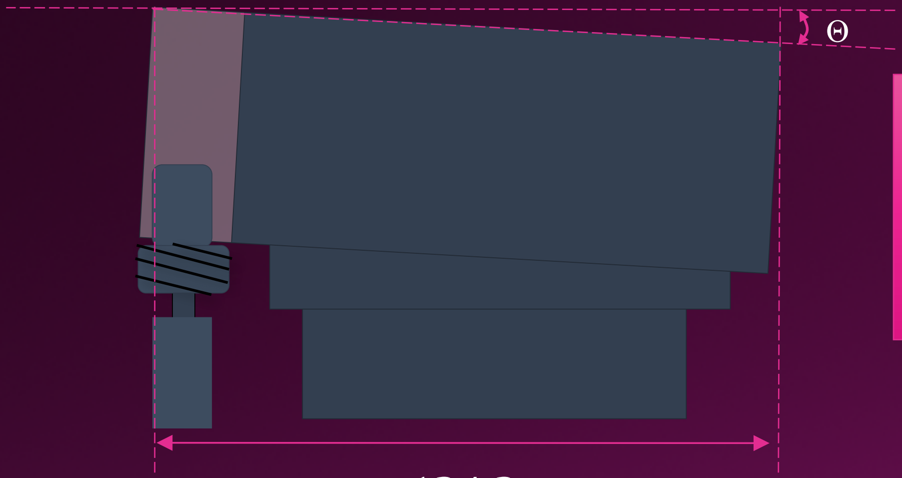
FR1 – Explanation

(working on drawing these in powerpoint)



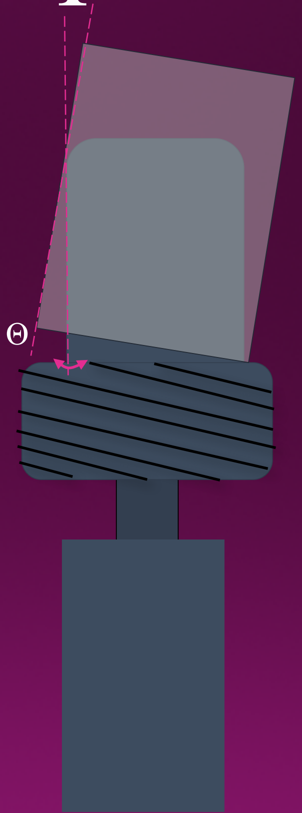


FR1 - Uneven Deployment Explanation



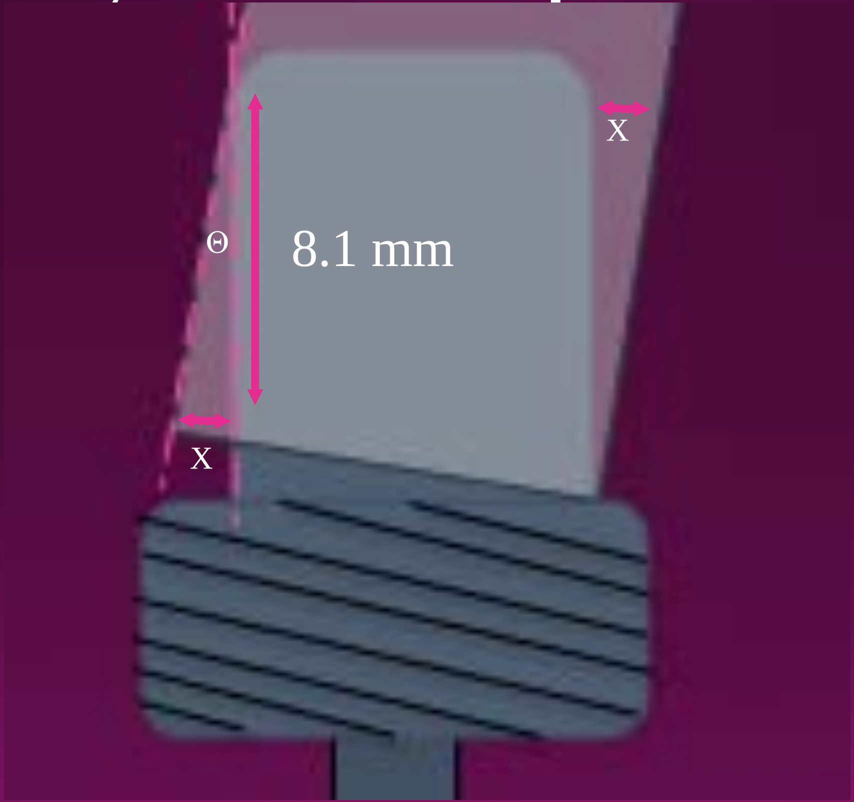
$$\theta = \tan^{-1}\left(\frac{5.2}{124.2}\right)$$

$$\theta = 2.4^{o}$$



FR1 - Uneven Deployment Explanation

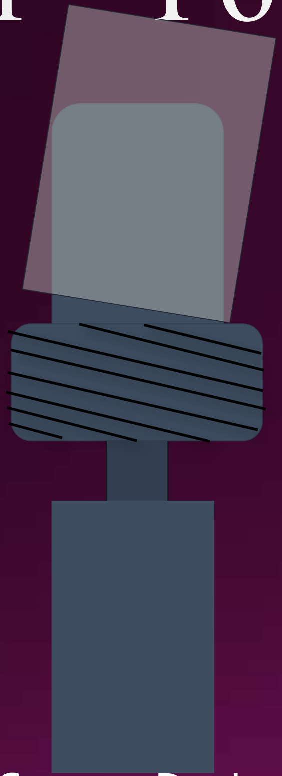
$$X = 8.1 * \tan(2.4^{o})$$
$$X = 0.34\,mm$$



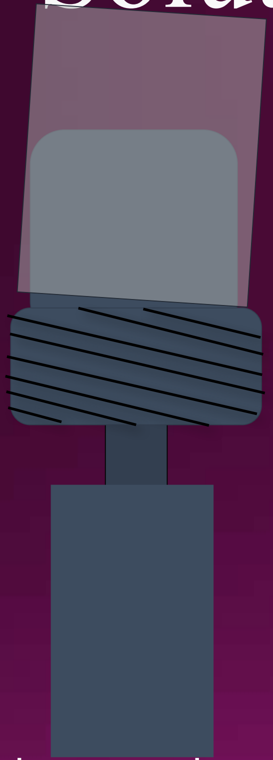
FR1 - Possible solutions

- These solutions are among some the final recommendations to our customer to make deployment more dependable, if they further develop the project
  - To fix the wobble a more rigid motor mount must be made
  - Manufacturing a new threaded rod would fix the uneven final position

FR1 – Possible Solutions



Current Design



Wider Non-threaded Rod Section

- Widening the non-threaded section would decrease the possible tilt experienced by the threaded casing
- This new width would be as close to the inner thread diameter of the casing as possible to manufacture

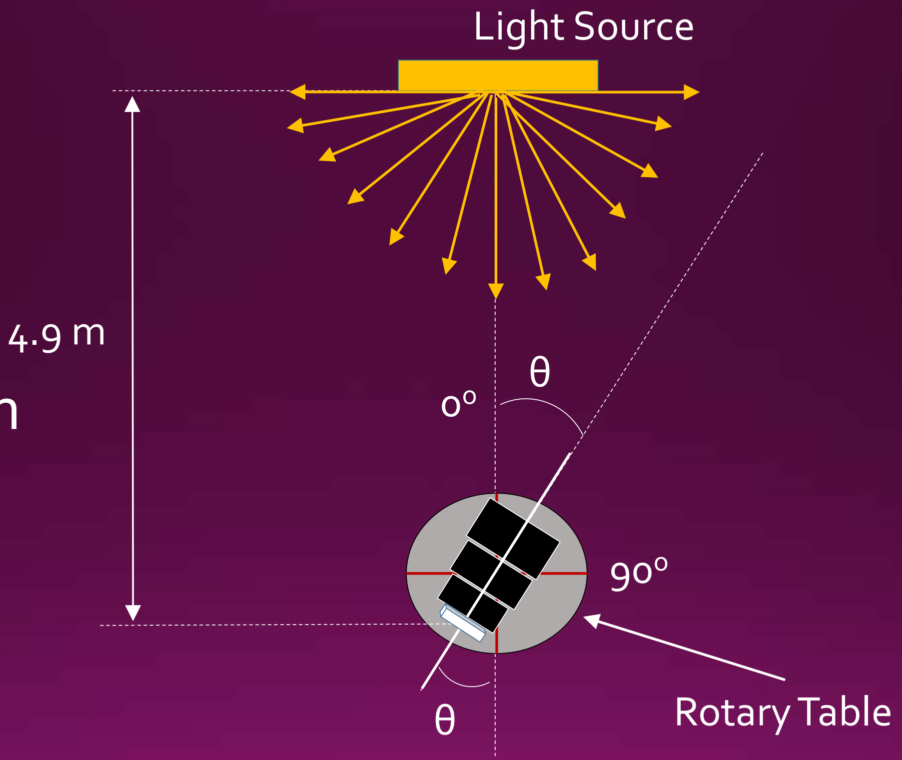
Test Results - Effect of Tilt

- Motor side deploys to the optimal height range
- Bearing side fails to fully deploy
  - Corresponds to widening the pre-obscuration angle on the bearing side by 0.555 degrees.

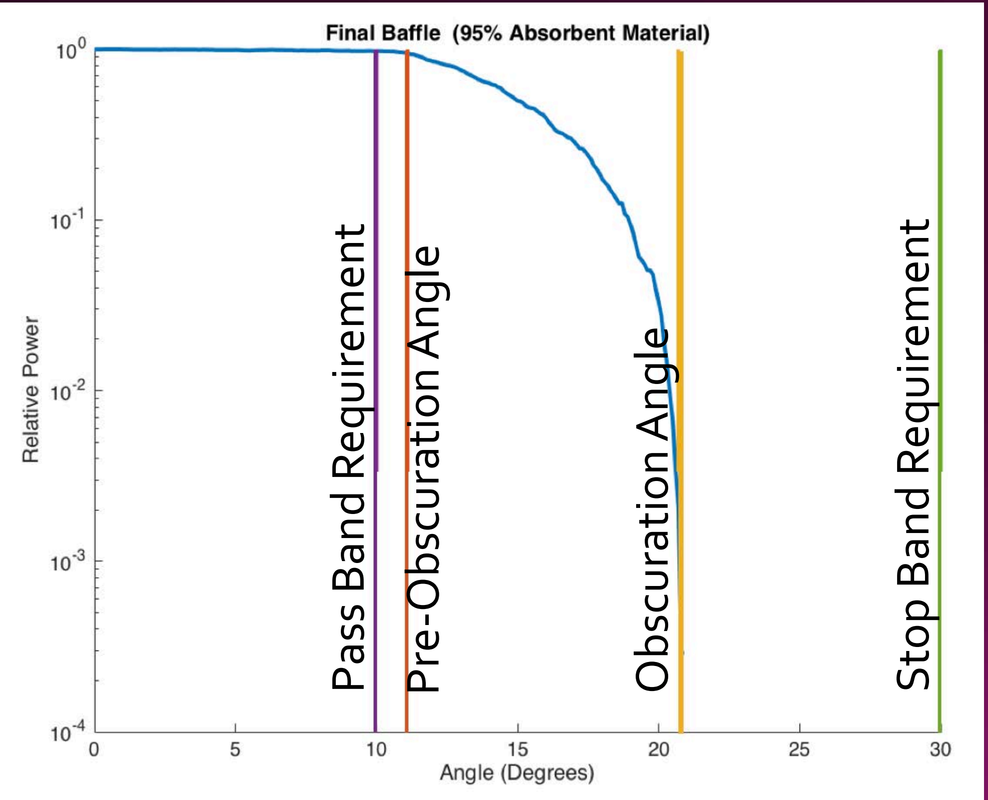
- Expected imperfect deployment, but expected our requirements to still be met
- Difference in height from motor side to bearing side corresponds to tilt of 0.555 degrees

Light Attenuation Test

- Will be testing light attenuation with respect to pointing angle
- Used to validate light attenuation requirements
- Can compare to Zemax data



Zemax Model Results

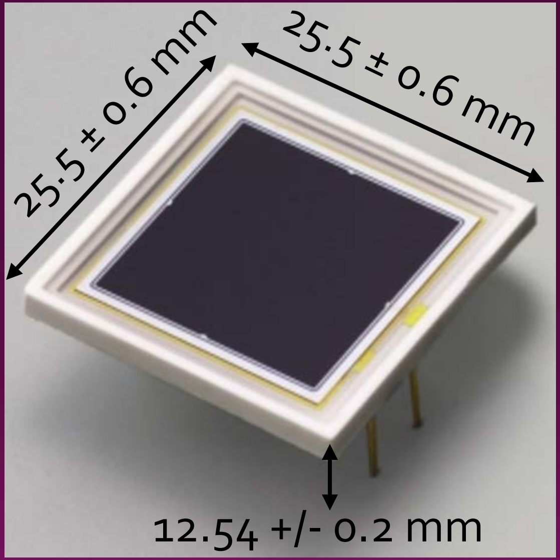


Critical Angles	Results
Pre-Obscuration Angle	11.1°
Obscuration Angle	20.8°

Data Collection & Post Processing

- DAQ connect to LabView Software
  - Photodiode generates current, current to voltage op amp circuit, LabView captures voltage
- Initial voltage measured at θ = 0 °
  - Voltage measurement taken every 4 ° from -90 to 90°
  - Taken every 0.1 ° for +/- 2 ° around requirements
- Power calculated from known resistance and measured voltage
- Relative power will be calculated

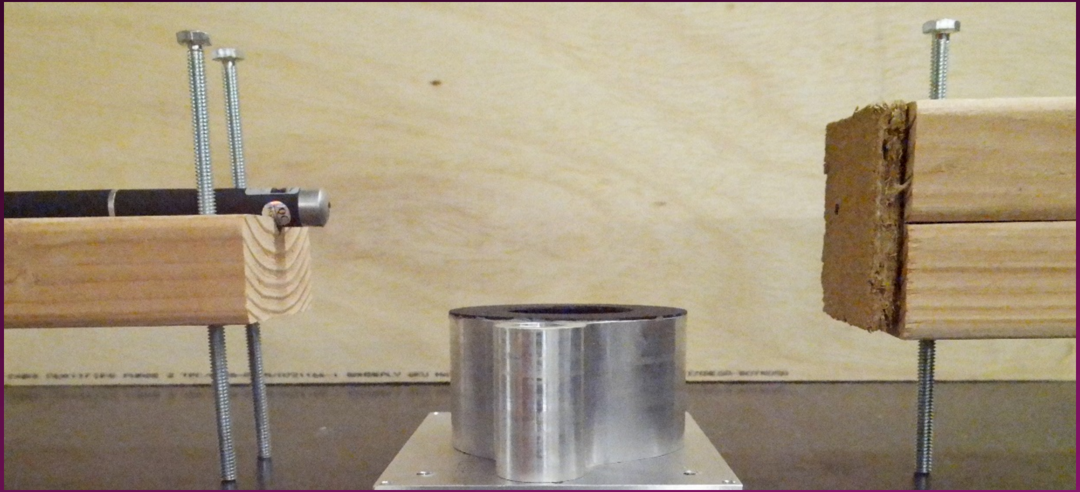
$$P_{rel} = \frac{P}{P_0}$$



Hamamatsu Photodiode [5]

Deployment Testing Overview

- Purpose
  - Ensure baffle deploys to necessary height for optical performance (>86mm)
  - Ensure baffle doesn't over deploy and damage it (<88mm)



Why this would change the game?

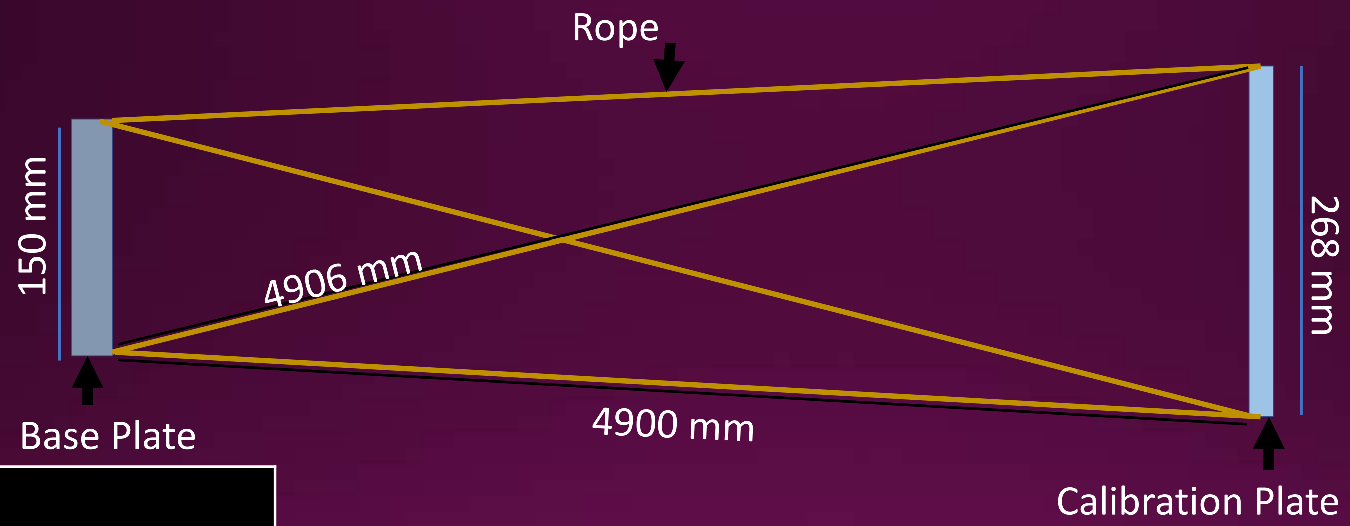
"There are plenty of cube-sat like star trackers, but many of them don't have the performance or flexibility to accommodate a lot of missions, and traditional fixed baffles take up too much space."

- Scott Taylor, Customer, Systems Engineer
Surrey Satellite Technologies


[6]

~ Half the mass, one third the size, but all the performance
~

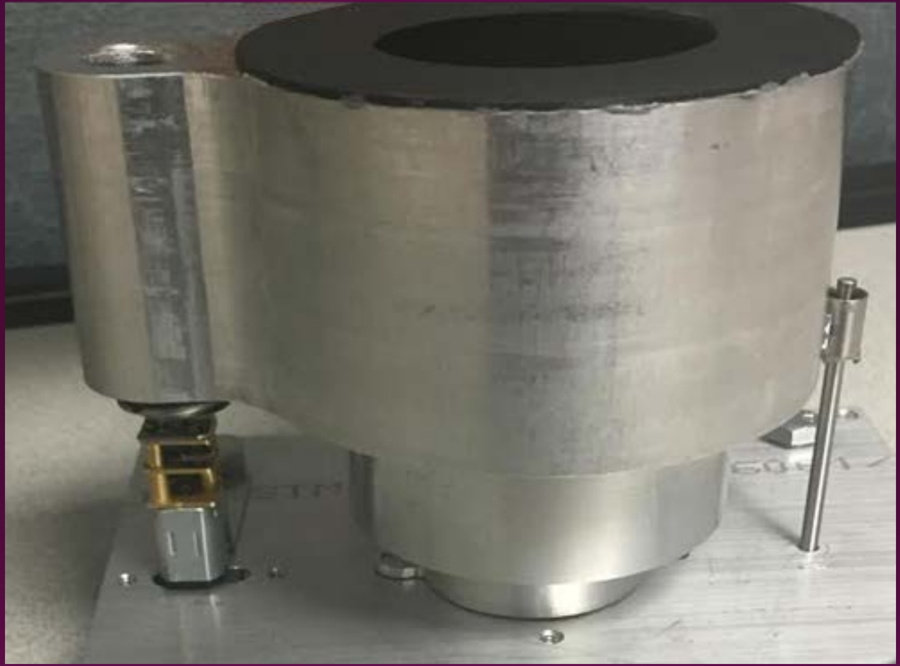
Calibration Method – Position



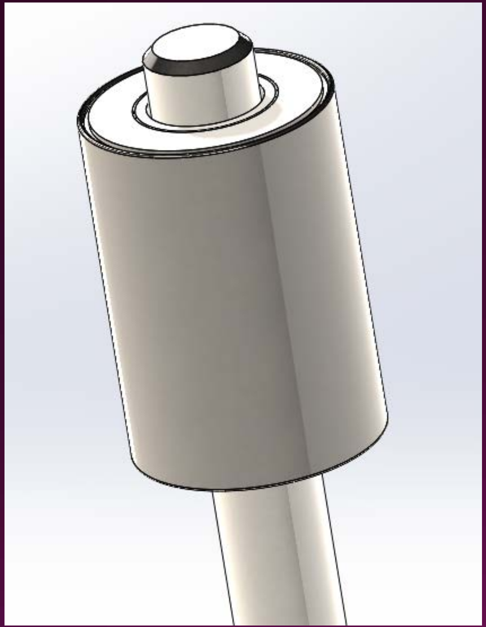
Rope Tolerance
Length: +- 200mm Changes FOV by <0.01°
Requirements
Apparent sun diameter = 0.05° Error: <2%

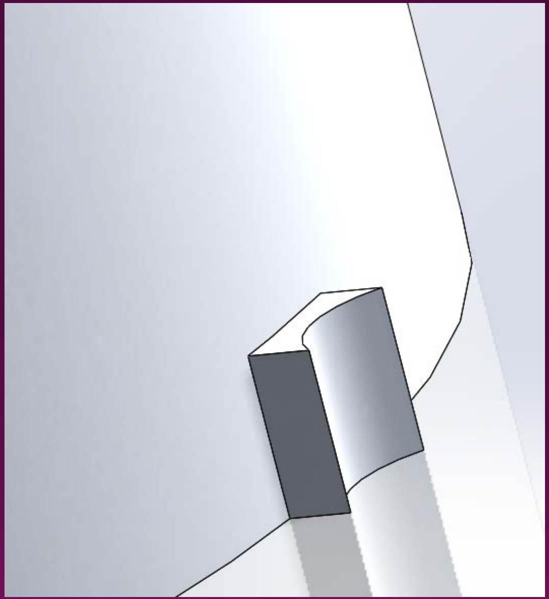
Accomplishments

- Current
  - Numerical model
  - Prototype deployable baffle
  - Deployment test suite
  - Light attenuation test suite
- By end of project (May 2017)
  - Experimental results
  - Verification and validation with Zemax data
- Follow-on Steps
  - Space worthy materials
  - Thermal testing
  - Vibration testing

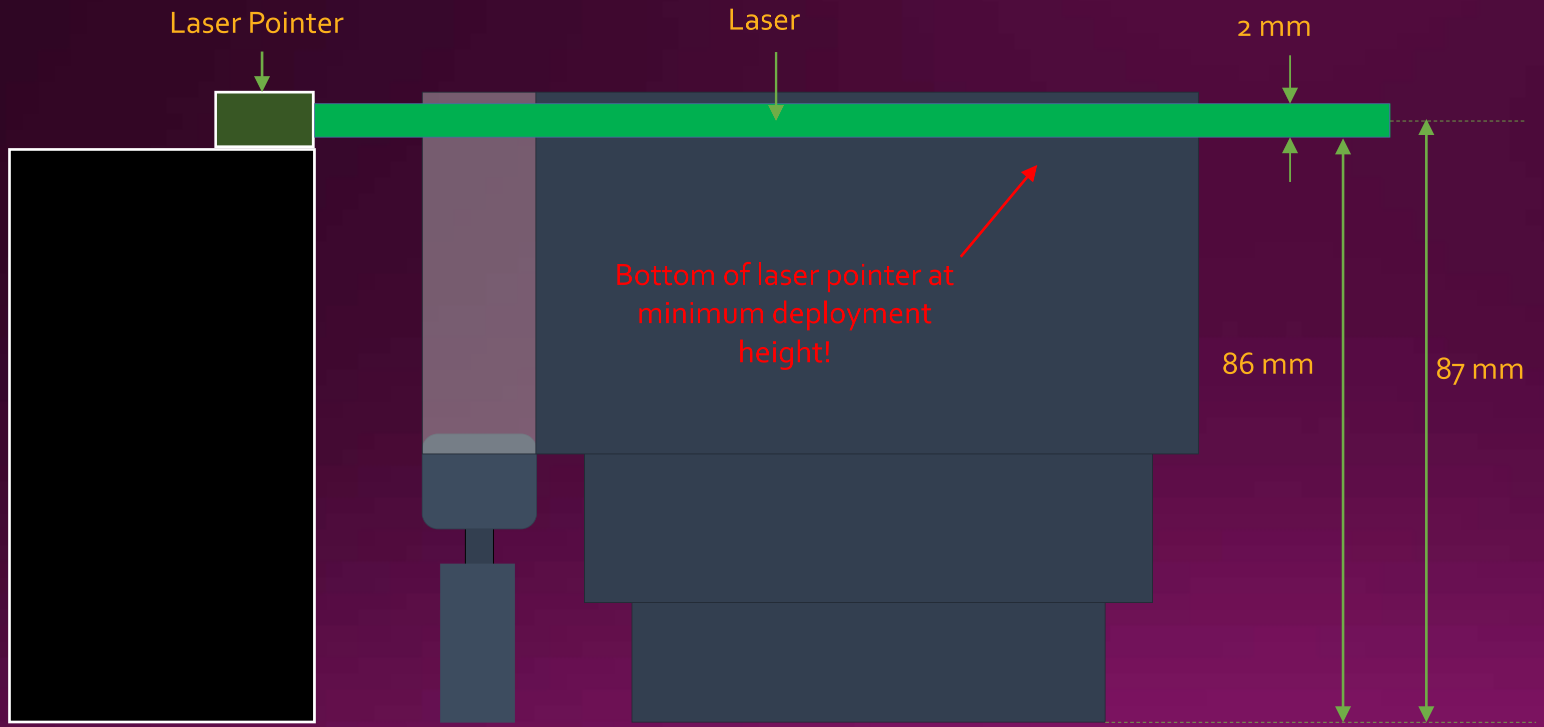


Linear Bearing





Deployment Testing



Requirements To Be Validated

- Light attenuation testing will verify both requirements
- Will be testing baffle symmetry and asymmetry

Requirement	Percent Light Attenuated	Angle (Degrees)
Pass-Band	5%	>10°
Stop-Band	99.9%	<30°

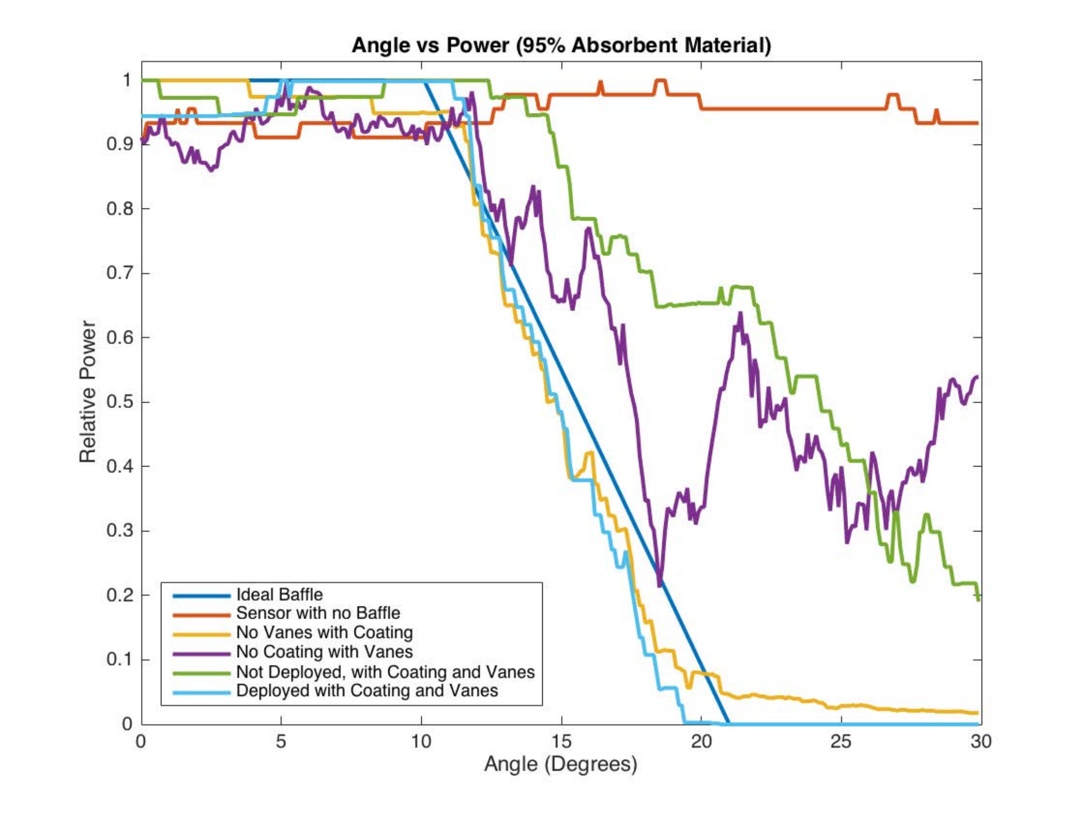
Light Attenuation Test Procedure

- Take initial power measurement, P_0, at 0°
- Take power measurements every 4°
- Between 8° and 12°, and 28° and 32°, measurements taken every 0.1°
- Test all baffle orientations

Space Readiness

- Proof of concept design and prototype
- Future Space Readiness concerns
  - Outgassing
  - Corrosion
  - Cold welding
- Mitigation plan
  - Aluminum alloy for baffle material
  - Space grade adhesive
  - Space grade motor and lubricant

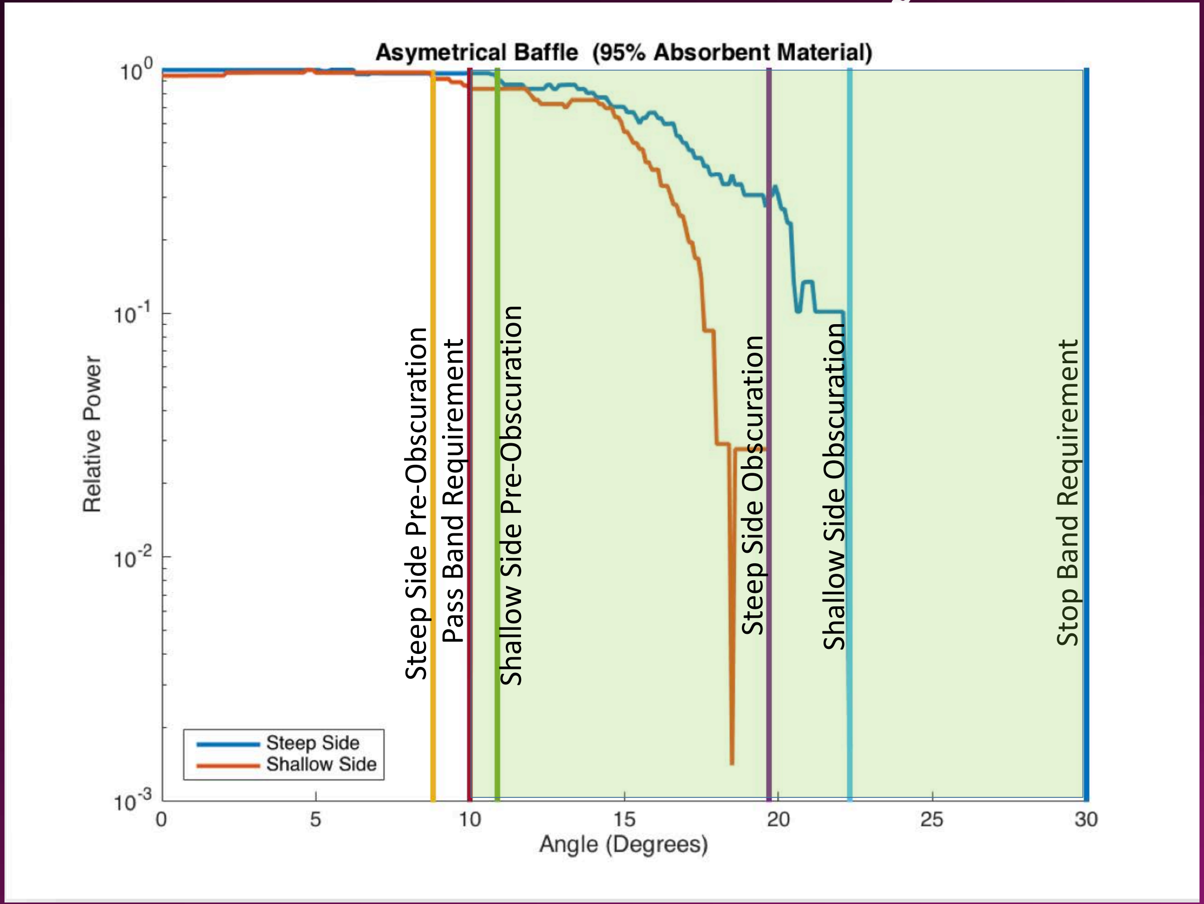
Design Decision Validation



Deployment Test Procedure

- Ensure bottom of laser pointer is at acceptable minimum deployment height
- Turn on laser pointer to start deployment
- When fully deployed, laser light to phototransistor will be impeded causing voltage to motor to stop ending deployment
- Repeat for maximum acceptable deployment height

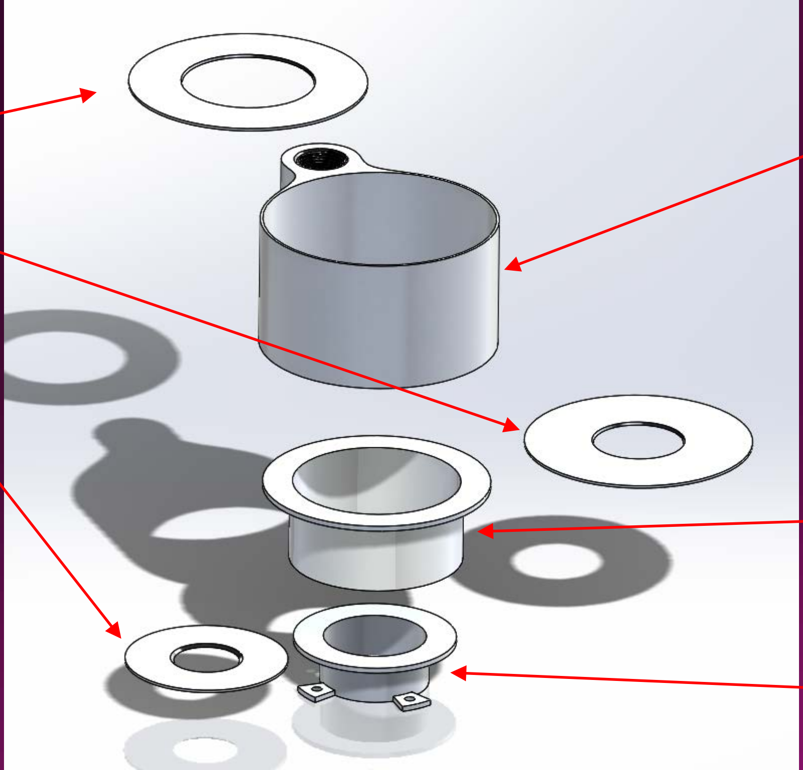
Zemax Validation – Asymmetric Model Results



	Steep Side	Shallow Side
Pre-Obscuration Angle	8.8	10.9
Obscuration Angle	19.7	22.3

Detailed Baffle Design

Vanes

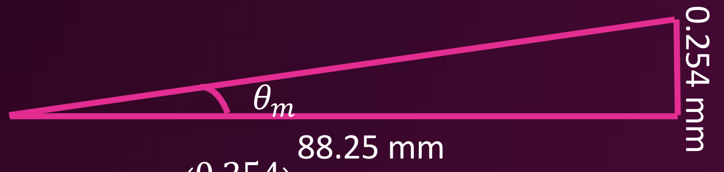


Top Section
H = 49mm
D = 86mm

Middle Section
H = 30mm
D = 62mm

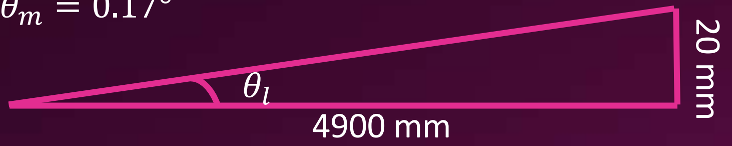
Bottom Section
H = 18mm
D = 38mm

Orientation Verification



$$\theta_m = \tan^{-1}\left(\frac{0.254}{88.25}\right)$$

$$\theta_m = 0.17°$$



$$\theta_l = \tan^{-1}\left(\frac{20}{4900}\right)$$

$$\theta_l = 0.23°$$

$$\theta = \theta_l + \theta_m$$

$$\theta = 0.23° + 0.17°$$

$$\theta = 0.40°$$