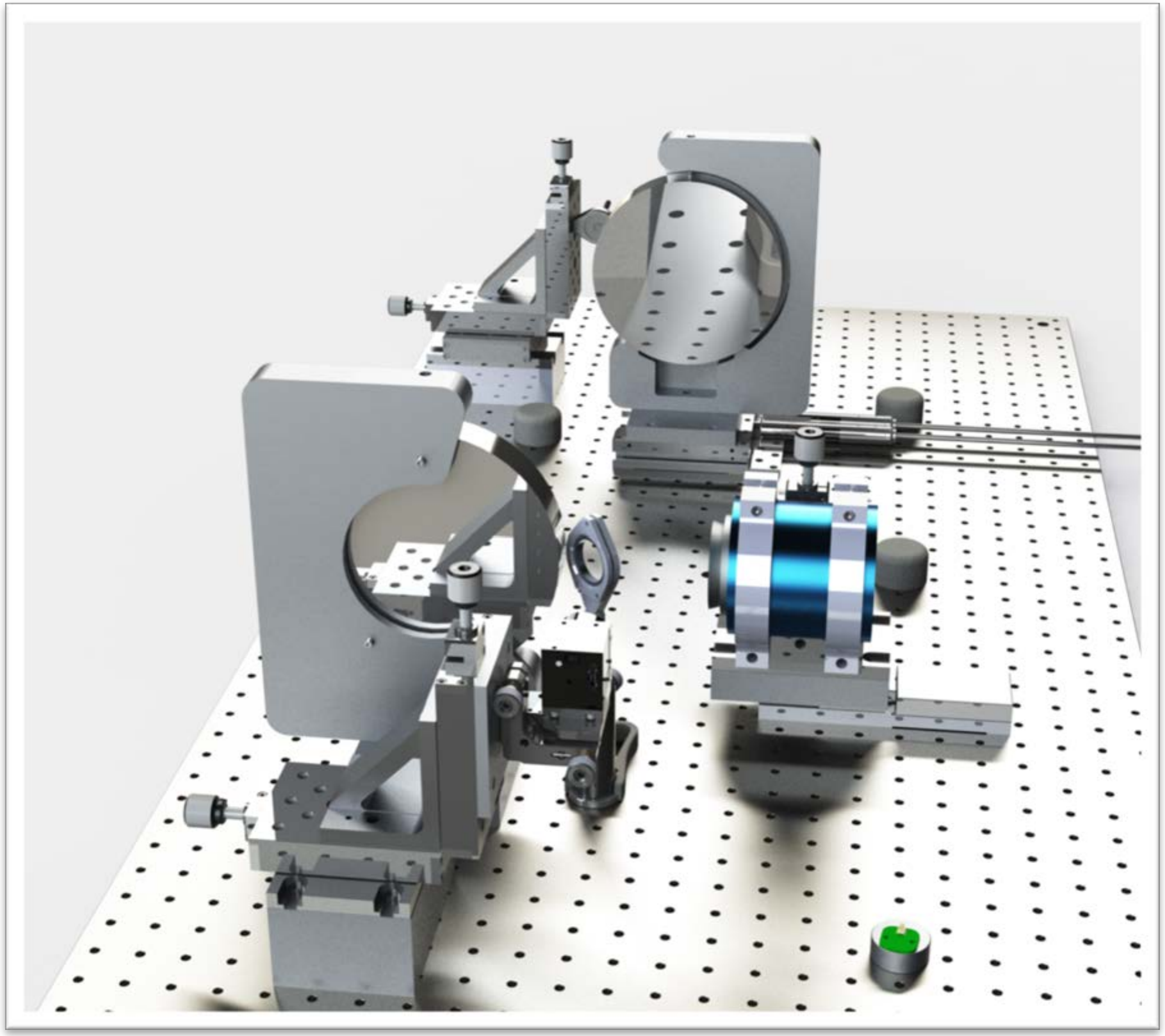
Apparatus for Wavefront Error Sensor Measurement:
Spring Final Review



April 26, 2018

Authors: Robert Belter, Ali Colic, Jake Crouse, Lucas Droste, Diego Gomes, Ankit Hriday, Owen Lyke, Brandon Noirot, Owen Shepherd, and Brandon Stetler

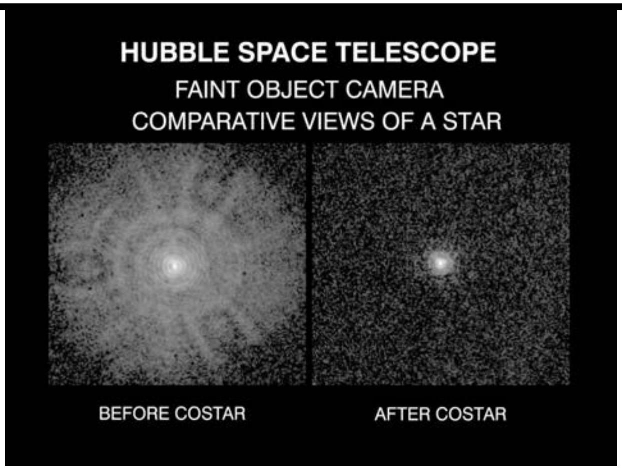
Customer: Eliot Young
Southwest Research Institute
&
NASA Glenn Research Center

1. PROJECT PURPOSE AND OBJECTIVES

1.1 – Background

Wavefront Sensing:

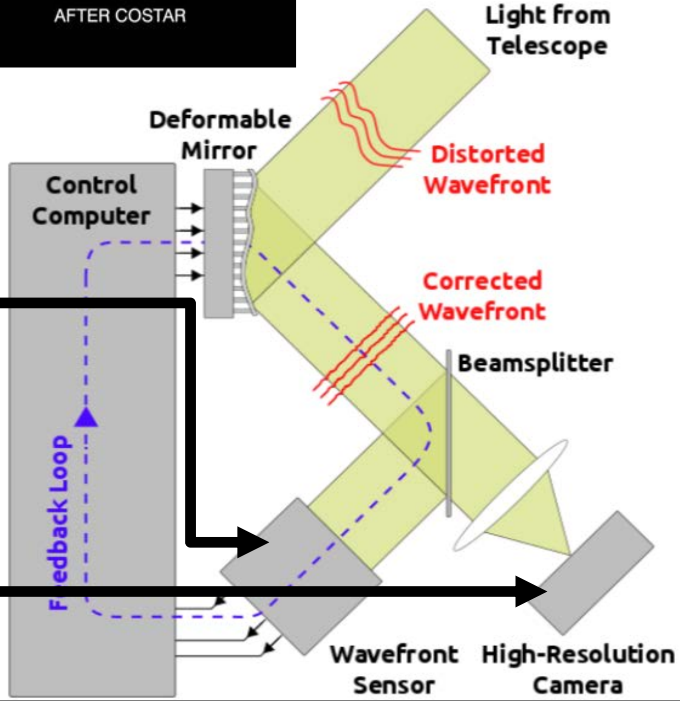
- A wavefront is a constant-phase surface of light emanating from a single source
- Wavefront error is non-uniform and induces distorted images



Corrective Optics Space Telescope Axial Replacement (COSTAR)

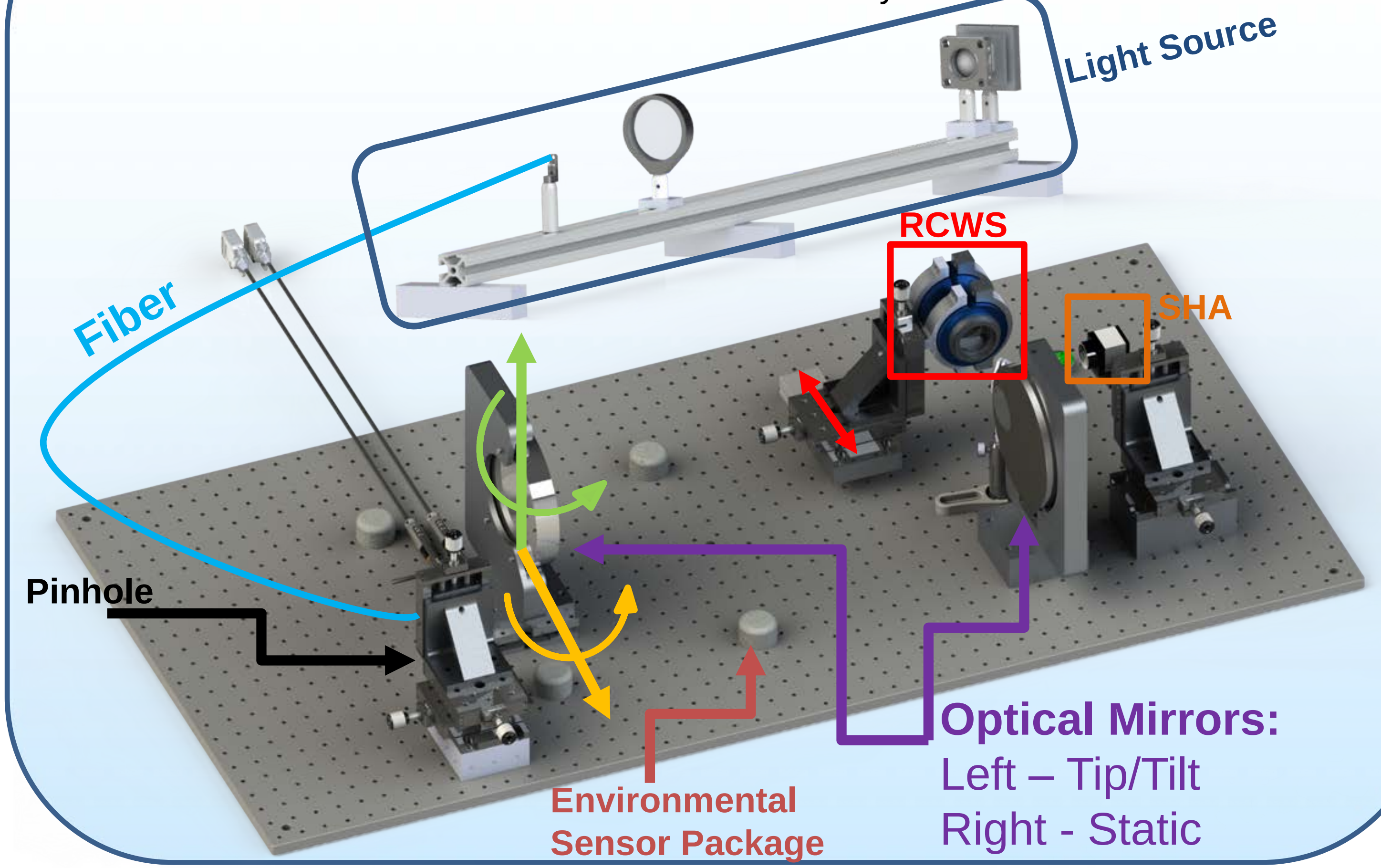
Wavefront Sensors (WFS):

- Used for feedback loop control on corrective devices
- Implementation on high-altitude balloons has potential to provide improved images
- **Shack-Hartmann Array (SHA):**
  - Heritage WFS platform
  - Requires access to Pupil (collimated beam) in optical system
- **Roddier Curvature Wavefront Sensor (RCWS):**
  - No additional hardware required, utilizes onboard camera
  - No requirement to modify the optical path
  - Unproven track-record



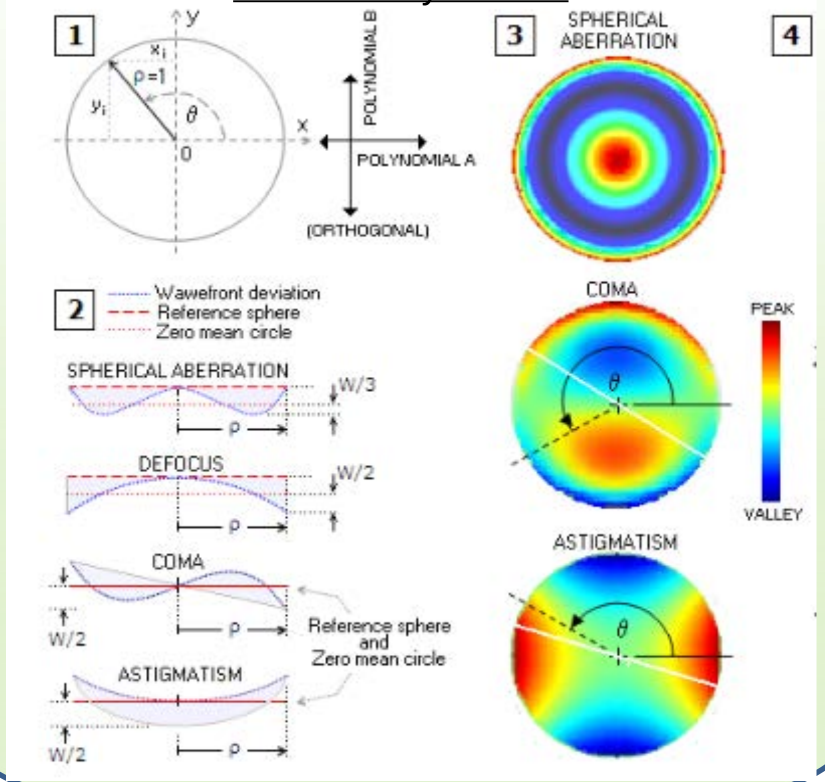
1.2 – Project Success

Level 1: Produce a lab-based testbed that collects *RCWS images*, *SHA data*, *environmental conditions*, and *varies* both *received light intensity* and *wavefront error* for wavefront analysis

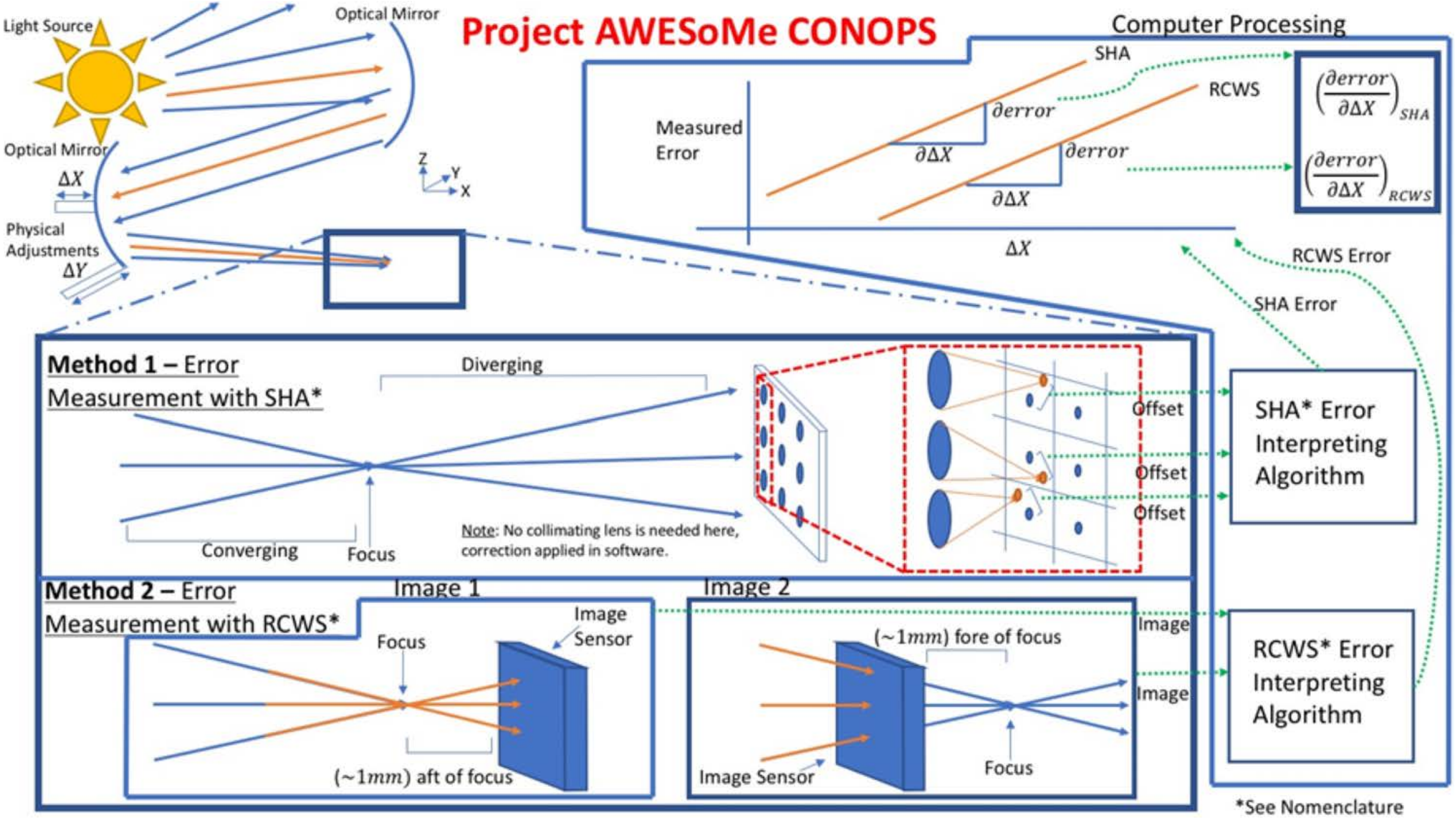


Level 2: Implement RCWS algorithm from Level 1 data and compare to SHA results expressed in the *rate of change of Zernike Polynomials* with respect to mirror movement

Zernike Polynomials

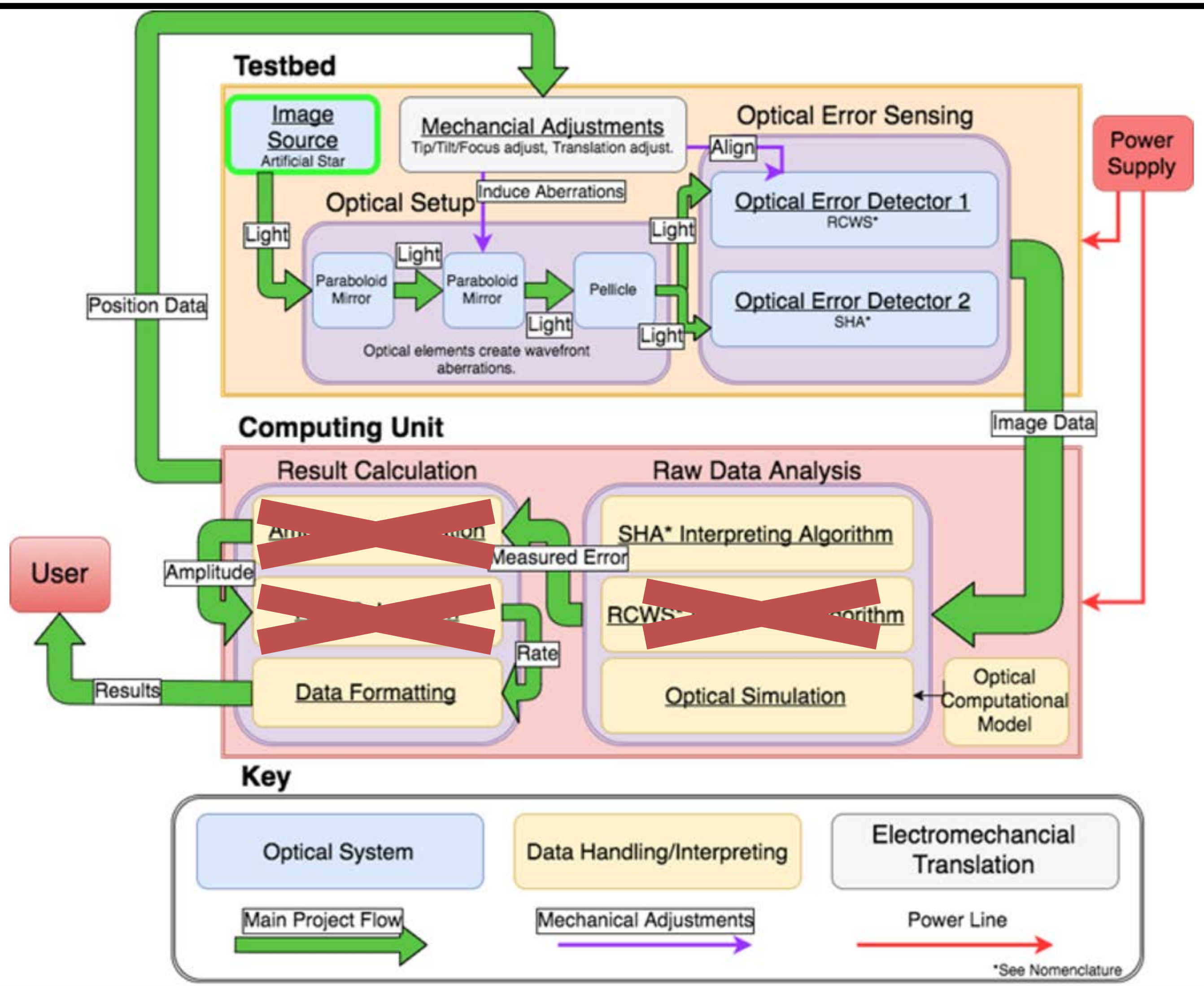


1.3 – Concept of Operations



2. DESIGN DESCRIPTION

2.1 – Functional Block Diagram



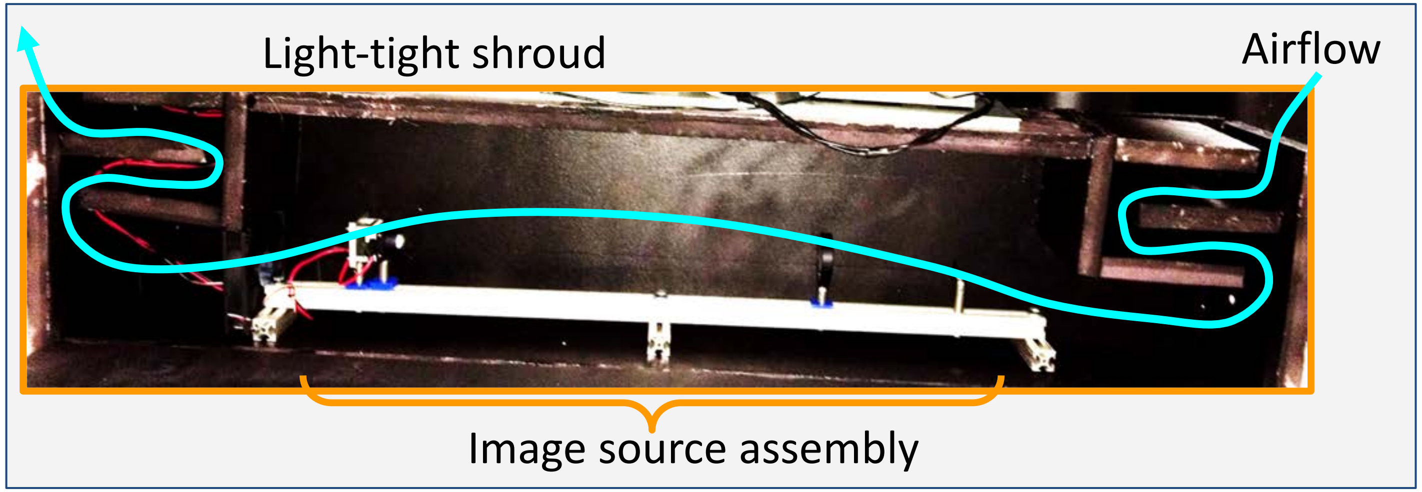
2.2 – Image Source

Design Requirements:

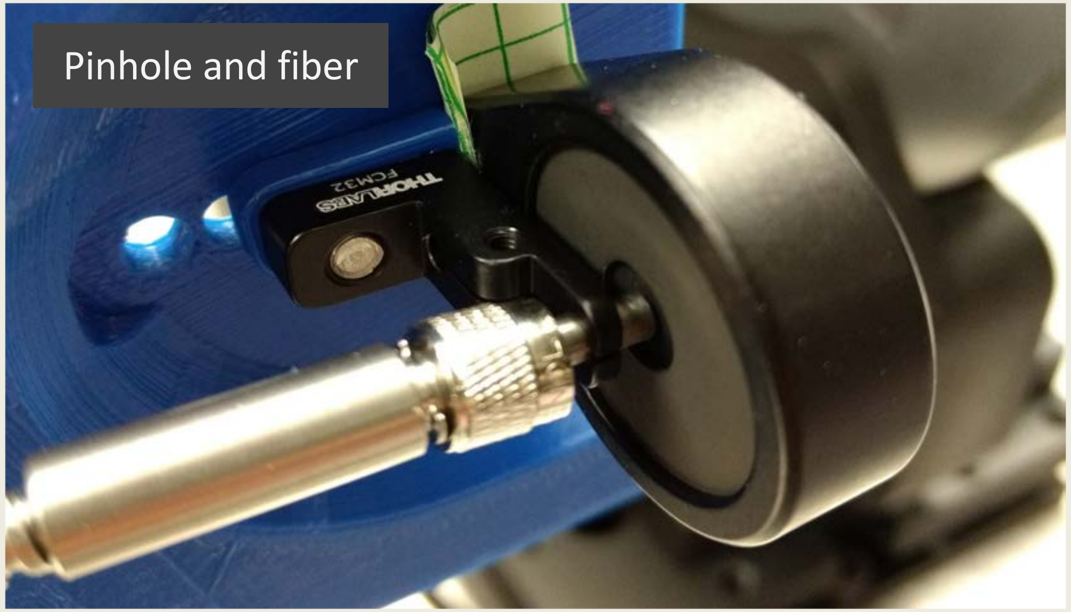
- Spherical wavefront (point source)
- Maximum pinhole size of 13µm
- 5e-08 watts of minimum output power
- Uniform intensity
- Vary received SNR
- LED cooling requirements

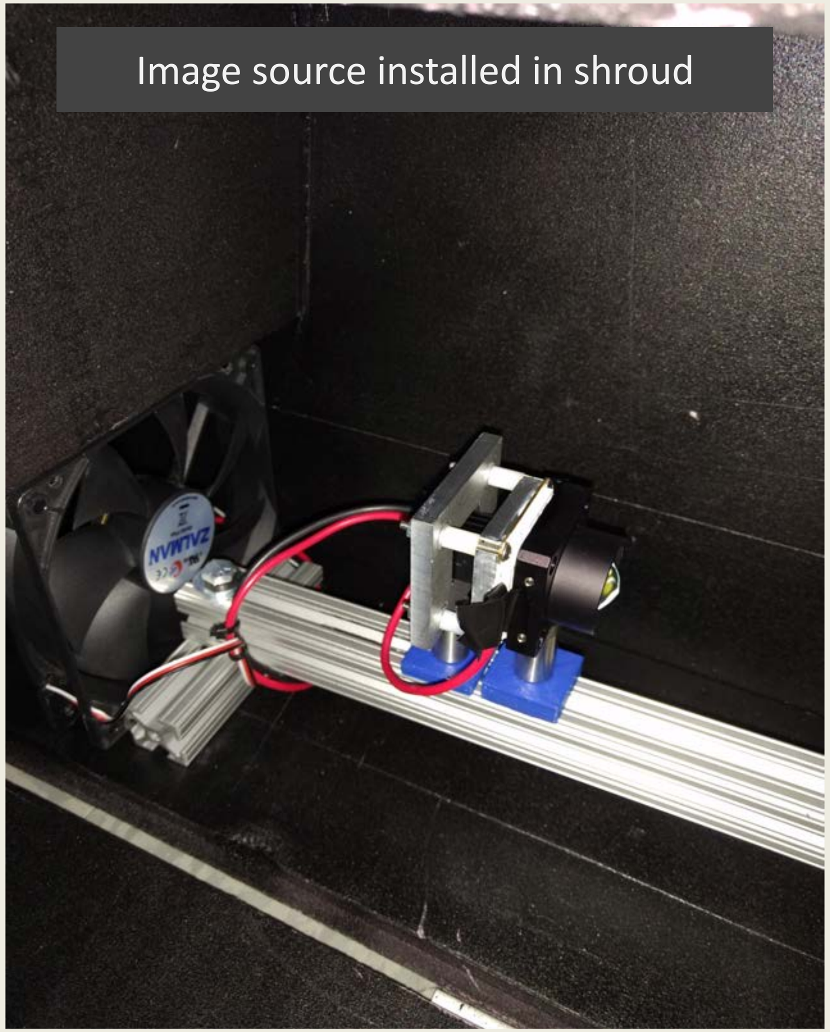
Design Solution:

- Custom-built to save costs (before budget increases)
- 100W LED and condenser lens increases intensity
- Fiber optic cable diffuses any possible images of the LED as well as removes heat and stray light source from testbed
- Received SNR varied by changing exposure time of detectors, image source constant.
- Shroud design allows cooling airflow but blocks light
- 10 µm pinhole simulates point source and is positioned at the focal point of M1



2.2.1 – Image Source





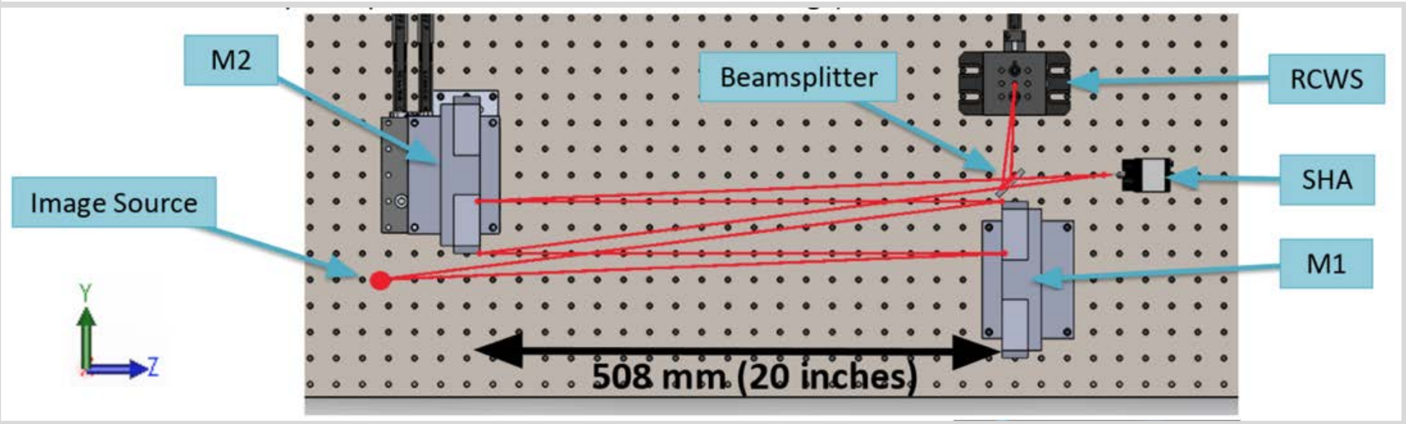
2.3 – Optical Path / Error Introduction

Design Requirements:

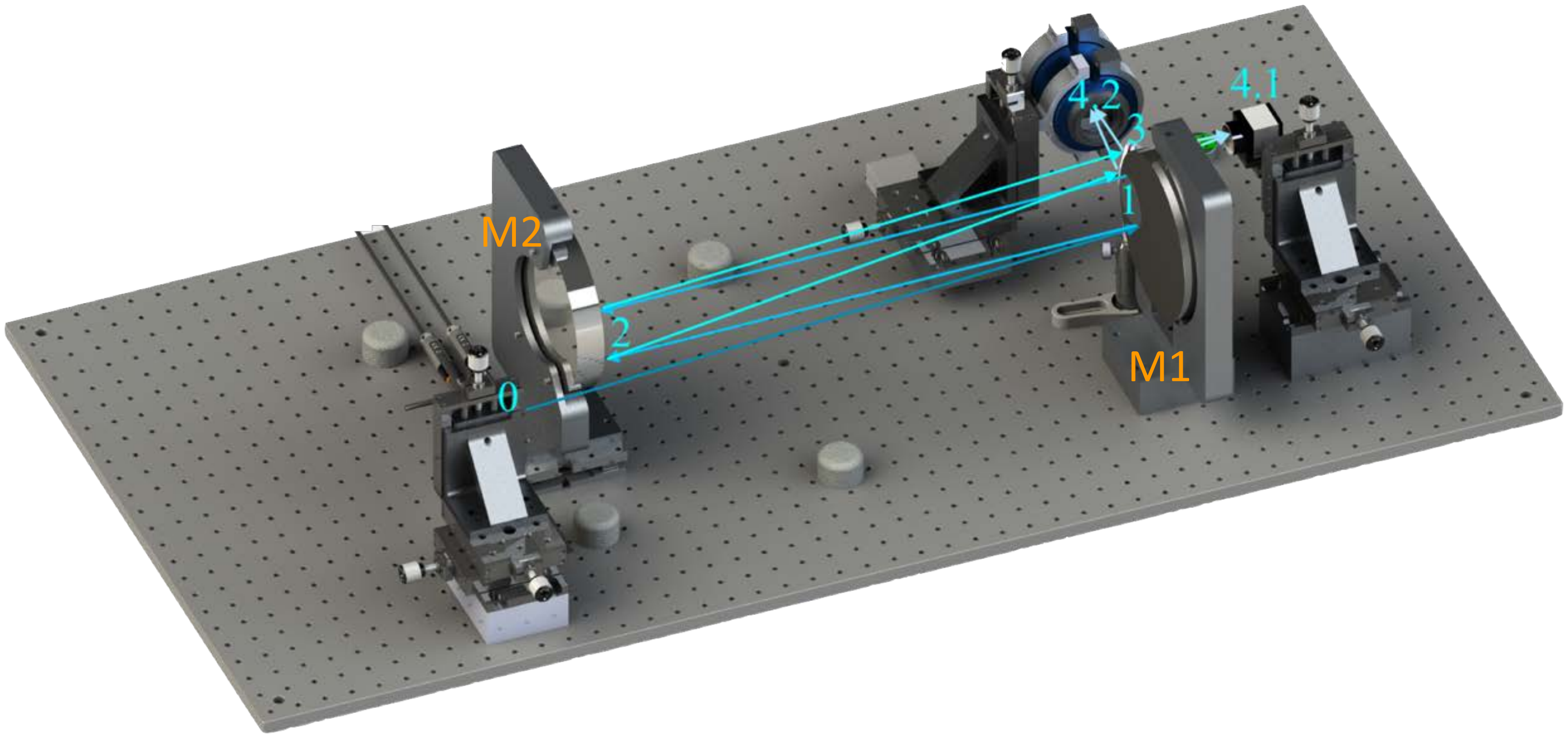
- Form an image for the detectors
- Introduce wavefront error with $\lambda/50$ RMS resolution or better
- Feed image to both detectors with minimal difference in wavefront

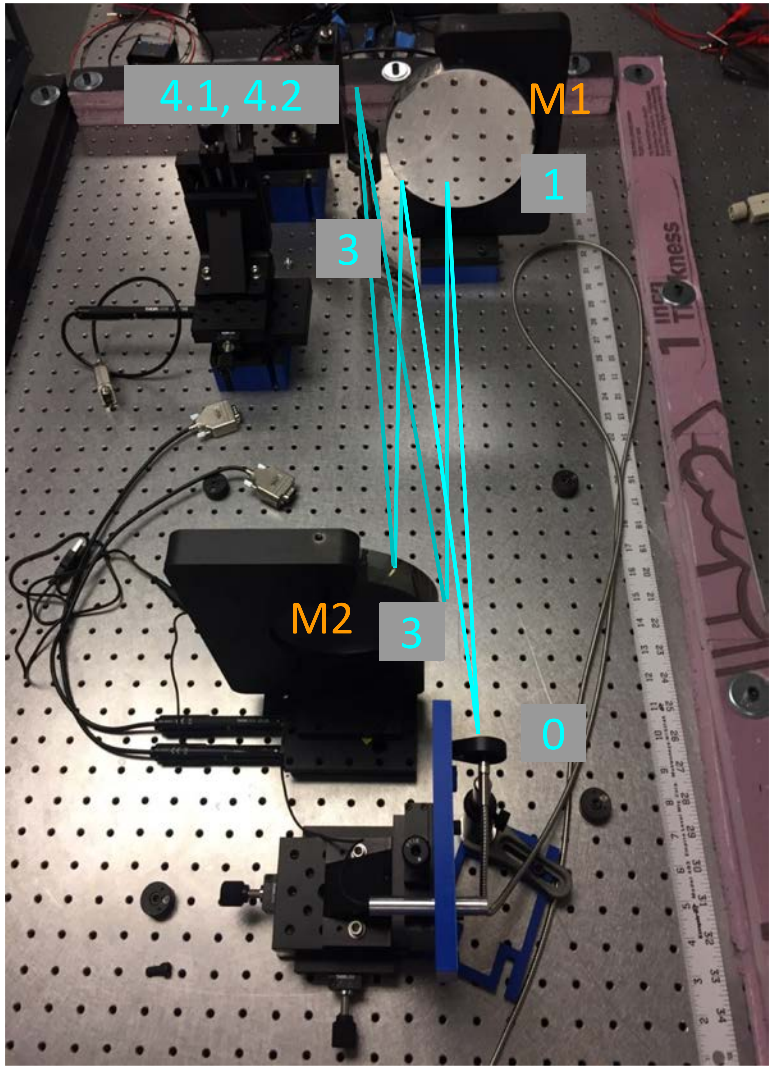
Design Solution:

- Customer-provided mirror arrangement focuses point source through two parabolic mirrors. 24” focal length places source and detectors outside of mirrors to allow for translation of the RCWS
- Custom mirror mounts designed to allow beam to pass directly by the edge of mirrors
- Thorlabs PY004-Z8 pitch/yaw platform selected to introduce error in up to $\lambda/2000$ RMS precision
- Pellicle beamsplitter introduces minimal differential error to sensors



2.3.1 – Optical Path Design and Implementation





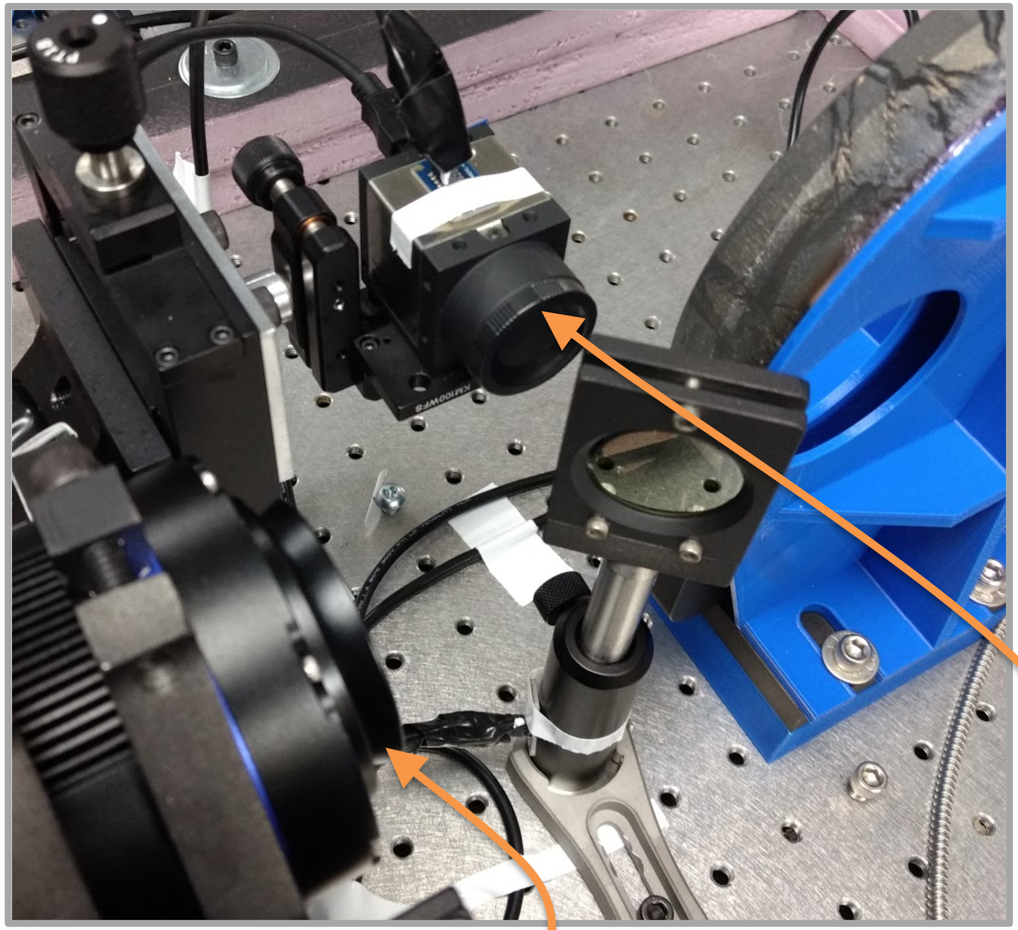
2.4 – Wavefront Sensors

Design Requirements:

- Comparison between RCWS and SHA methods

Design Solution:

- Compare sensors on response rate to reduce alignment needs
- Use provided WFS150-7AR SHA as 'truth' measurement
- Use QHY174M detector and PT1-Z8 translation stage to implement RCWS method
- Pellicle beamsplitter feeds both sensors with minimal difference in wavefront
- Account for difference in received light intensity through pellicle in post-processing



RCWS Detector (QHY174M) ThorLabs SHA (WFS150-7AR)

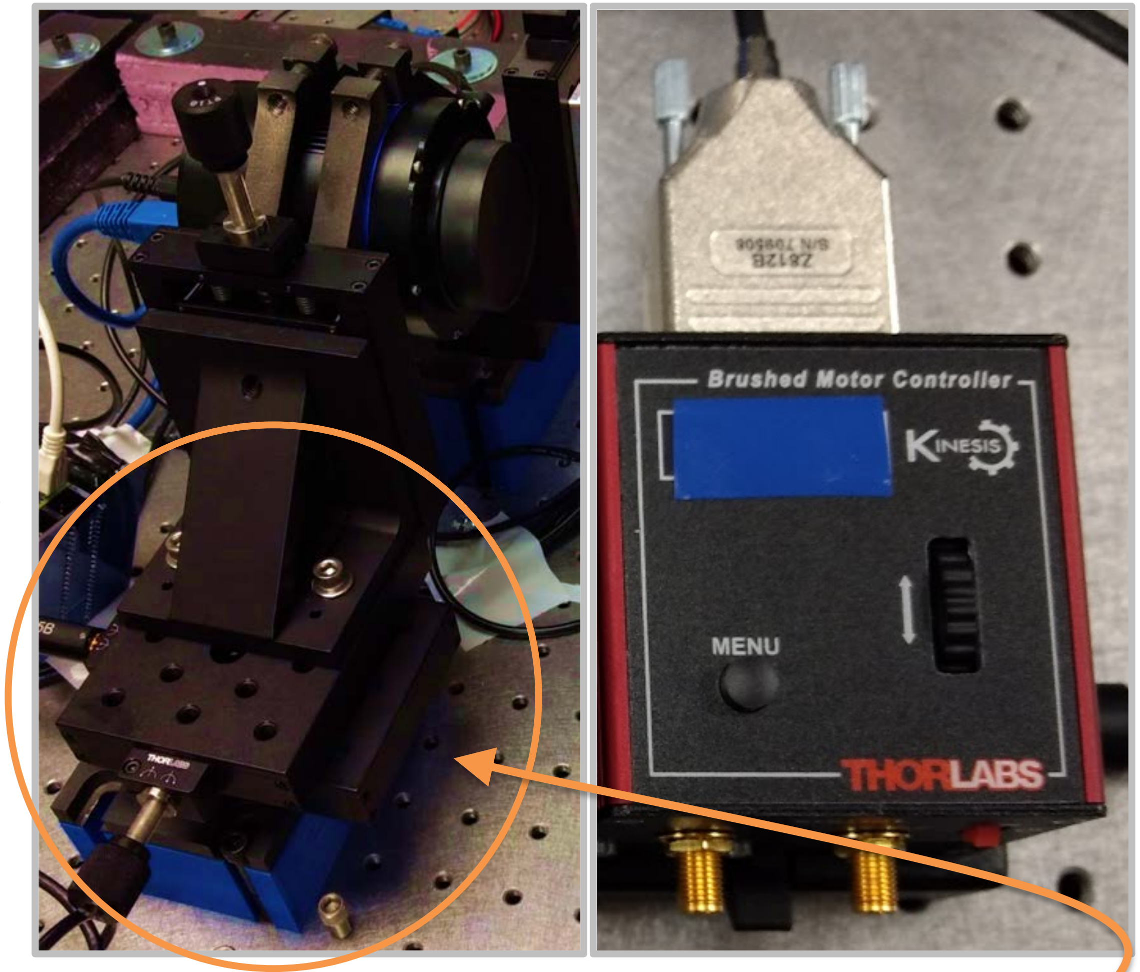
2.5 – Testbed Automation

Design Requirements:

- Three degrees of variation: wavefront error, SNR, and RCWS defocus distance
- Automated process to collect large sets of data and reduce human error
- Generated data shall include all data required to perform comparison between RCWS and SHA

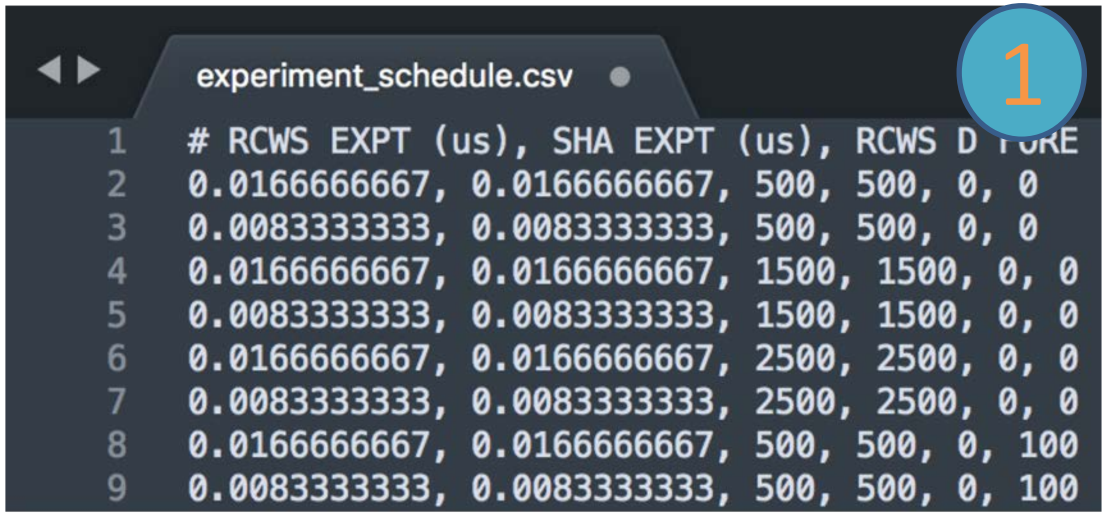
Design Solution:

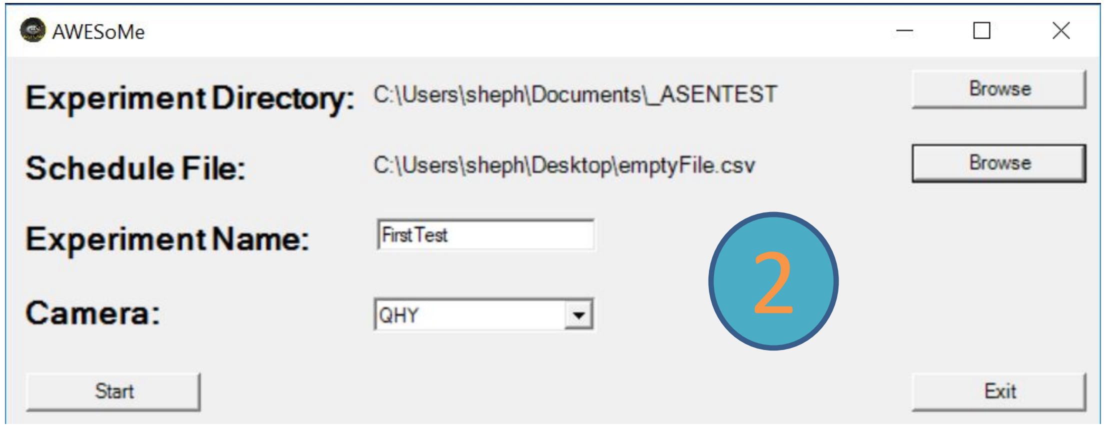
- ThorLabs motorized optical stages for tip/tilt and linear traverse
- ThorLabs API usage for motor controllers and SHA data collection
- ASCOM API for reading RCWS detector
- Serial stream-to-file of environmental data
- Atomic file structure generation to preserve all relevant data in manageable sizes
- All combined into single test control program written in C# that takes a user-specified experiment schedule
- External MATLAB / Zemax interface generates expected wavefront from optical model in post-processing

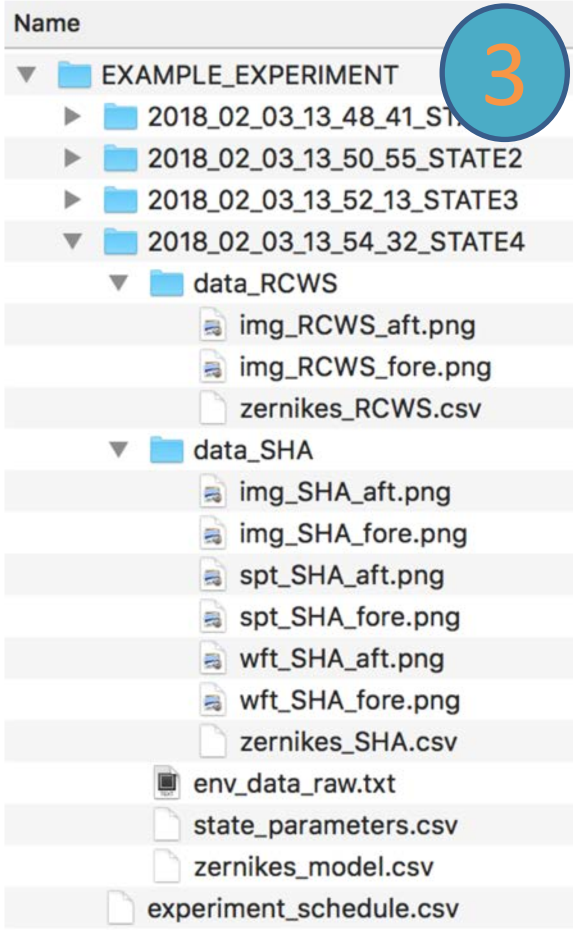


Motorized linear traverse below RCWS detector

2.5.1 – Software Interface and Data Organization







1. Specify experiment parameters
2. Choose output directory and experiment schedule file
3. Results are generated automatically
   1. All data required to compare sensors included
   2. Data for a given system state collected in individual folders along with the parameters of that particular state
   3. Experiment schedule file copied into main folder for records

3. TEST OVERVIEW AND RESULTS

3.1 – Level 1 Success Fulfillment Criteria

Criteria	Tests Complete	Addtl. Testing for PFR
Introduces wavefront error with $\lambda/50$ RMS resolution in order to be within accuracy of the SHA sensor	Measure introduced tip/tilt resolution	Verify Zemax model using SHA, re-test considering hysteresis
Quantifies the precision of RCWS movement in order to drive TIE error propagation	Measure linear movement resolution of RCWS stage	None
SNR varies down 8 octaves from the maximum value in order to compare sensors' low-light performance	Validate SNR variation model by controlling exposure time	Re-test in sub-10us exposure regime
Performs tests automatically according to user specifications and organizes resulting data	Ability demonstrated in course of other system verification tests	None

Many additional sub-tests and unit verifications were performed throughout the process of integration.

3.2 – Tilt/Tip Platform Resolution

Purpose:

Prove that tip/tilt platform meets minimum required resolution of 260 arcseconds, as predicted by Zemax to introduce $\lambda/50$ RMS wavefront error.

Required Equipment:

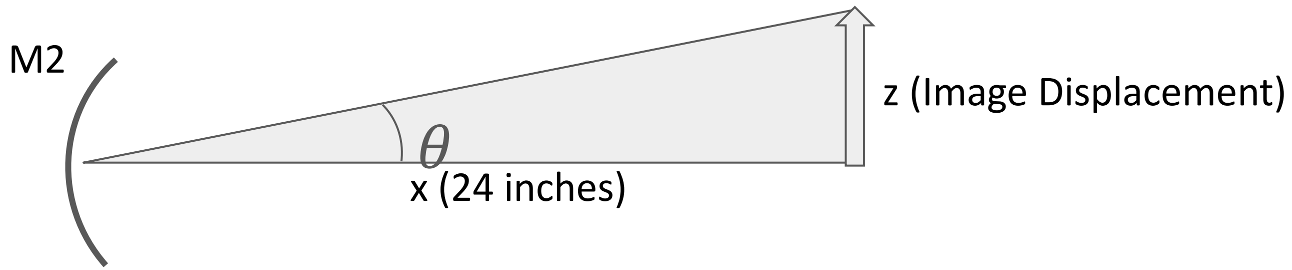
Laser, neutral density filter, CMOS, Tilt/tip platform

Method:

With the laser mounted above the yaw axis of the tilt tip platform, introduce tilt and tip and measure the displacement of the image across the CMOS sensor.

$$\theta = arctan\left(\frac{z}{x}\right)$$

$$\delta\theta = \left[\left(\frac{-z}{z^2+x^2}\right)^2(\delta x)^2 + \left(\frac{x}{z^2+x^2}\right)^2(\delta z)^2\right]^{1/2}$$



3.2.1 – Mirror Yaw Control Results

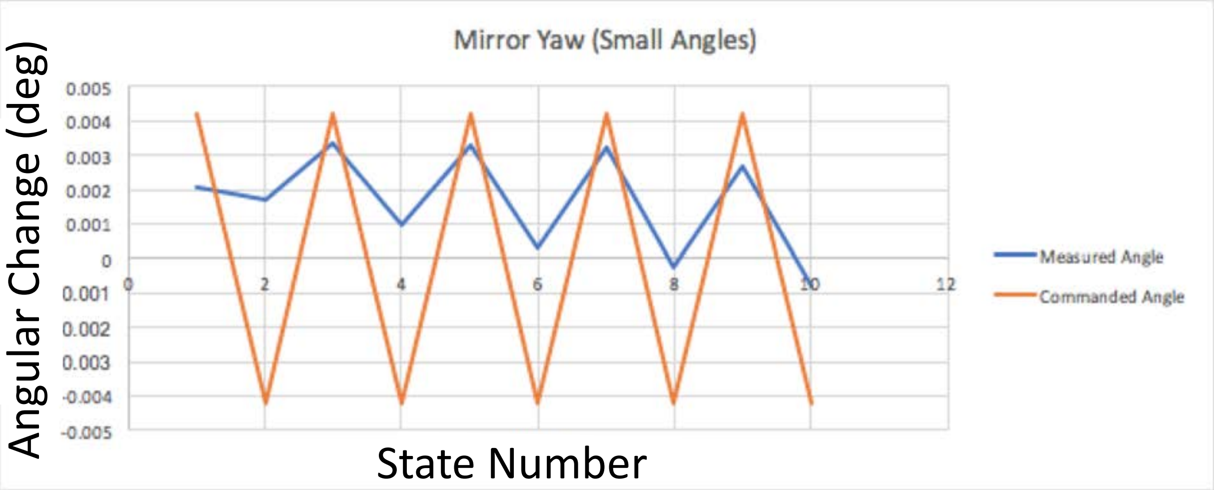


Image moving across detector by tip/tilt of M2

- Hysteresis prevents the platform from rotating back for small commanded angles
- Homing returns to reference reliably
- Additional testing will confirm uni-directional precision

Average Error (arcsec)	Standard Deviation (arcsec)
10.44	6.48

Requirement	Description	Motivation
2.2.1	Wavefront error shall be introduced in resolution equal to or exceeding a RMS optical path delay of $\lambda/50$	Ability to out-perform stated specifications of SHA reference sensor

3.2.2 – Mirror Pitch Control Results

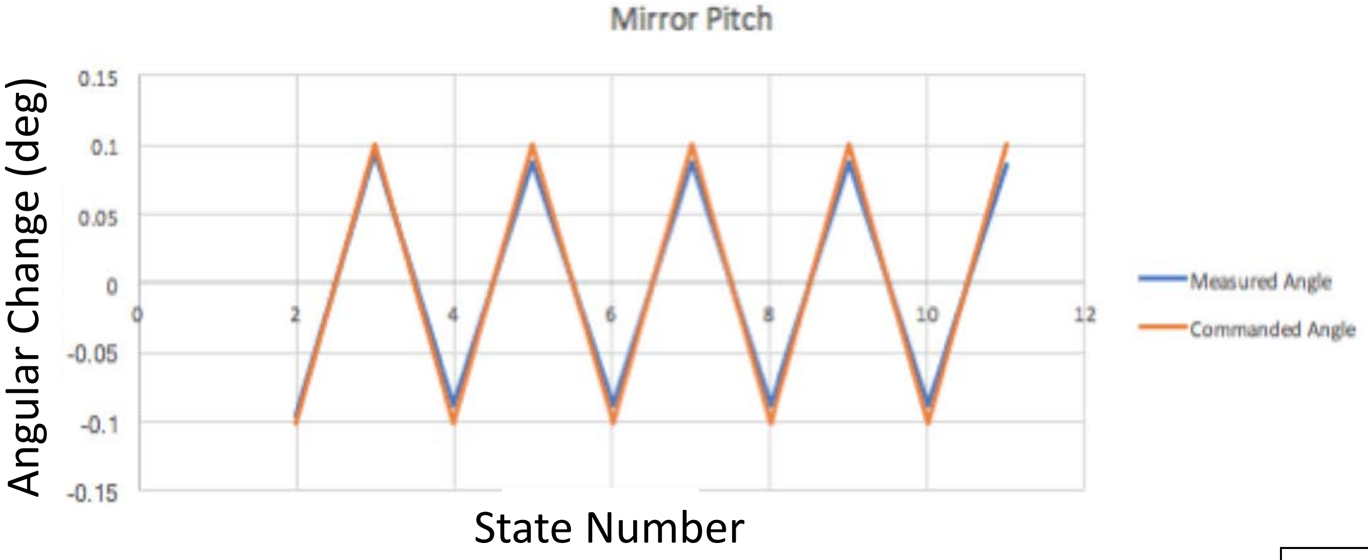


Image moving across detector by tip/tilt of M2

- Pitch control does not exhibit hysteresis like the yaw axis
- Precision is well below required 260 arcsec figure
- Additional testing will directly confirm $\lambda/50$ precision using the SHA

Average Error (arcsec)	Standard Deviation (arcsec)
39.96	11.448

Requirement	Description	Motivation
2.2.1	Wavefront error shall be introduced in resolution equal to or exceeding a RMS optical path delay of $\lambda/50$	Validating rotational accuracy of pitch/yaw stage.

3.3 – Linear Traverse resolution

Purpose:

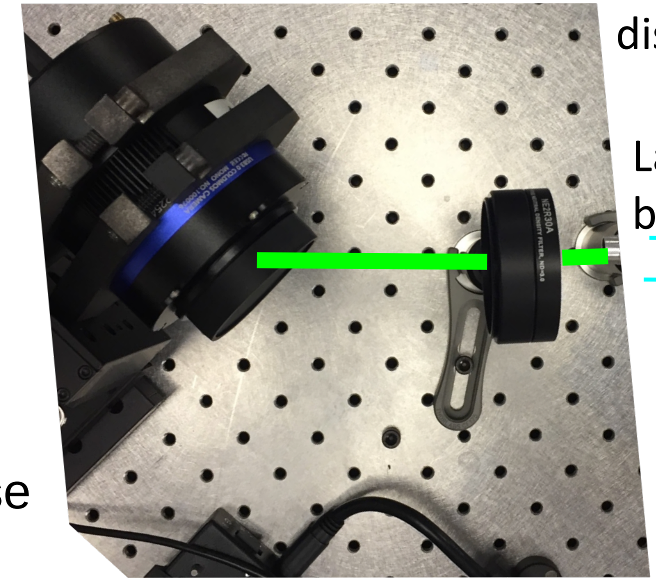
- Verify precision of RCWS stage
- Enable TIE error propagation

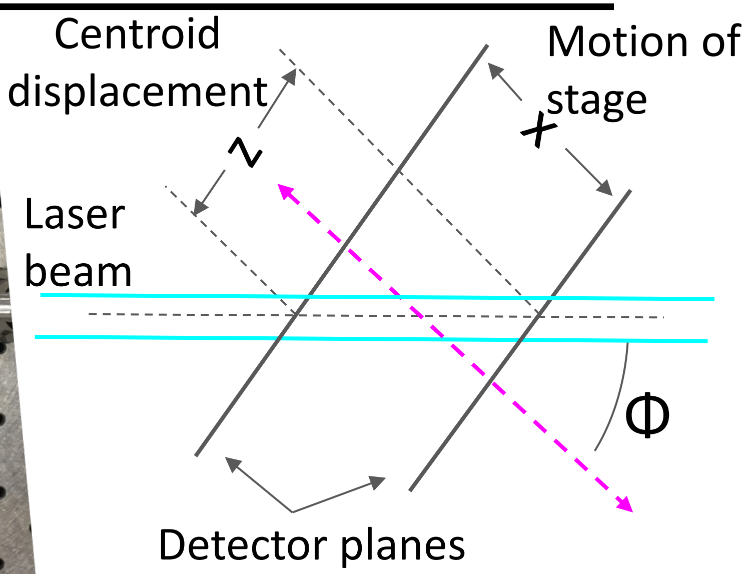
Required Equipment:

Laser, neutral density filter, CMOS, Linear Traverse

Method:

With the laser mounted in a single position pointing at the CMOS, translate the CMOS to 1mm and measure the displacement of the image across the CMOS sensor.

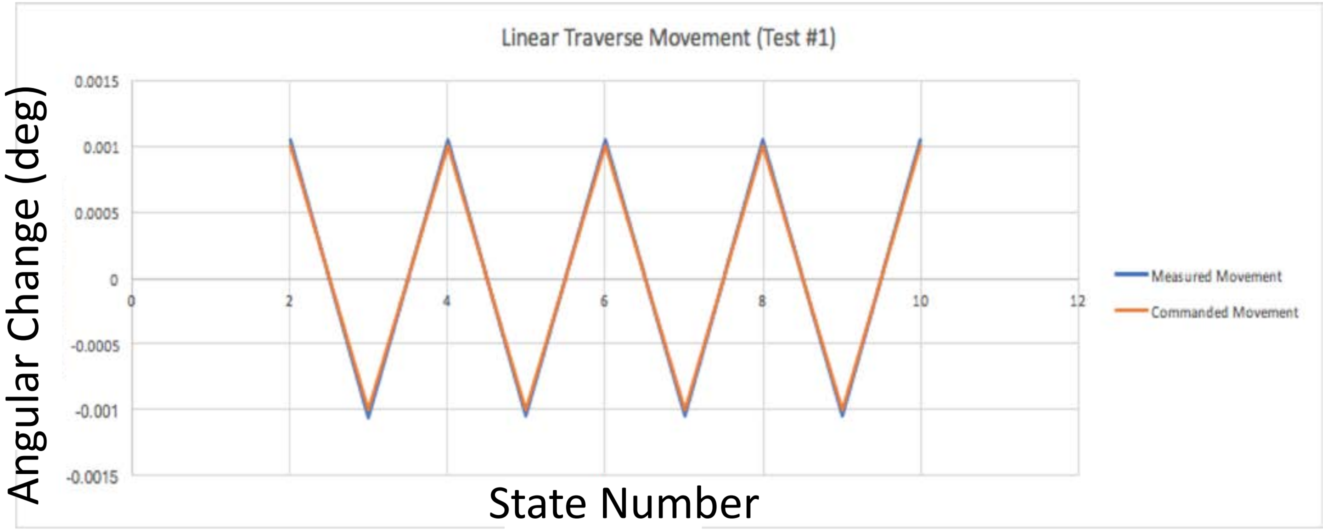




$$x = \frac{z}{tan(\phi)}$$

$$\delta x = \left[\left(\frac{1}{\tan\phi}\right)^2(\delta z)^2 + \left(\frac{-z\sec^2\phi}{\tan^2\phi}\right)^2(\delta\phi)^2\right]^{1/2}$$

3.3.1 – Stage Translation Results



Spot size changing as RCWS slides between planes

- Consistent movement in the stage
- More test-induced error than error in the stage
- Resulting information will be used by researched to propagate error in the transport of intensities equation

Average Error (um)	Standard Deviation (um)
500	499

Req.	Description	Motivation
3.3	The precision of the RCWS defocus movement shall be quantified	Informs scientists of how error stackup is affected by the defocus distance term in the TIE

3.4 – Signal to Noise Ratio (SNR)

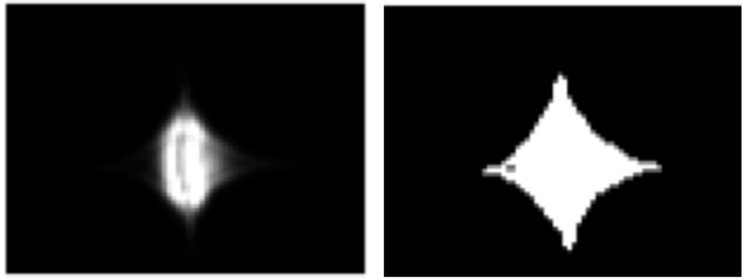
$$SNR \approx \frac{S}{\sqrt{S + N_c^2}}$$

Purpose:

Verify model of SNR variation with change in exposure time and satisfy minimum of at least 100 SNR at maximum exposure time

Signal image, threshold mask

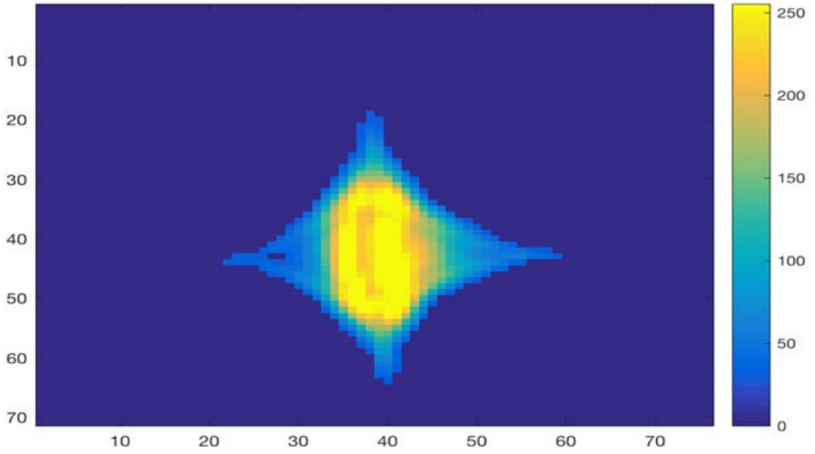
Signal image (L)
Threshold mask (R)



Required Equipment:

Full testbed setup

Pixelwise SNR

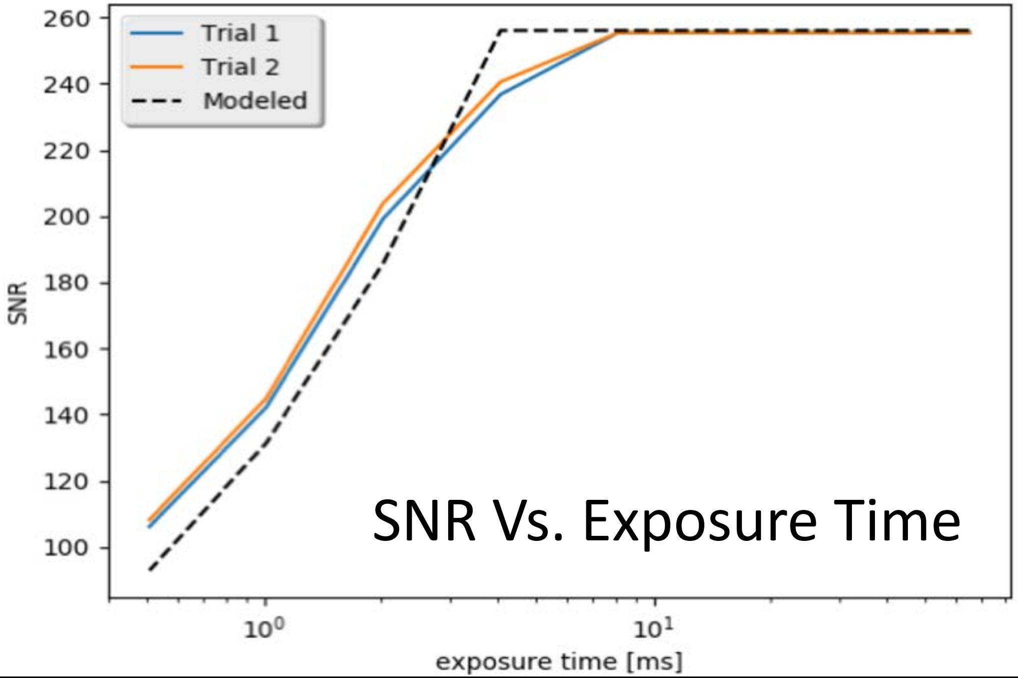


Method:

- Take images on RCWS decreasing the exposure time over 8 octaves beginning with 65 μS, with the source both on and off
- Perform thresholding to determine where the image is
- Compute pixel-wise SNR, then take average

3.4.1 – Signal to Noise Ratio Results

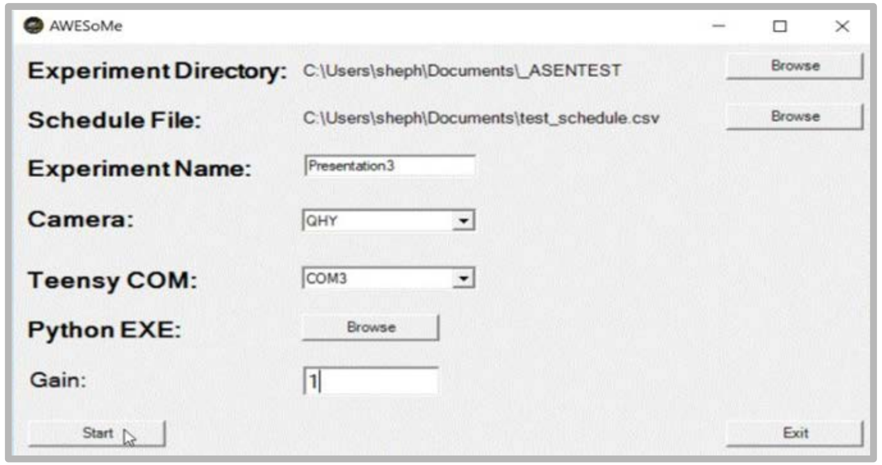
- Test results run at set exposures and defocus distances with the source on and off to calculate SNR.
- 100 SNR attained, exposure time viable control of SNR
- Clipping at high SNR due to saturation of image sensor
- Ability to cover 8 octaves not demonstrated.
- Additional testing will employ a combination of:
    - Image source intensity reduction
    - Exposure times below 10us



SNR Vs. Exposure Time

Requirement	Description	Motivation
3.1	A minimum 100 SNR for image sensors at maximum exposure time.	Testing in realistic light conditions.
3.2	Energy received by sensors shall diminish by increments of half until 1/128th of maximum.	Testing in realistic light conditions.

3.5 – Testbed Automation Results



Automation Software GUI

- Automated software runs tests as expected
- Current implementation helps cut runtime to an average 1 min per trial from ~5 min

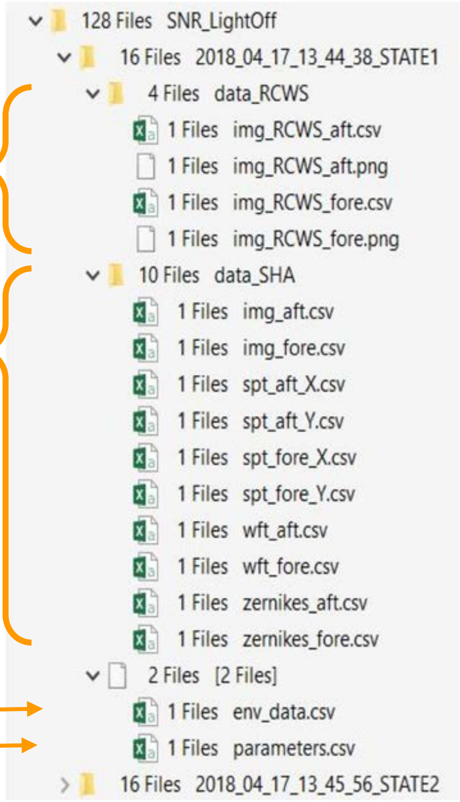
Total Experiment Data

RCWS Testbed Data

SHA Testbed Data

Environmental Data

Test Parameters



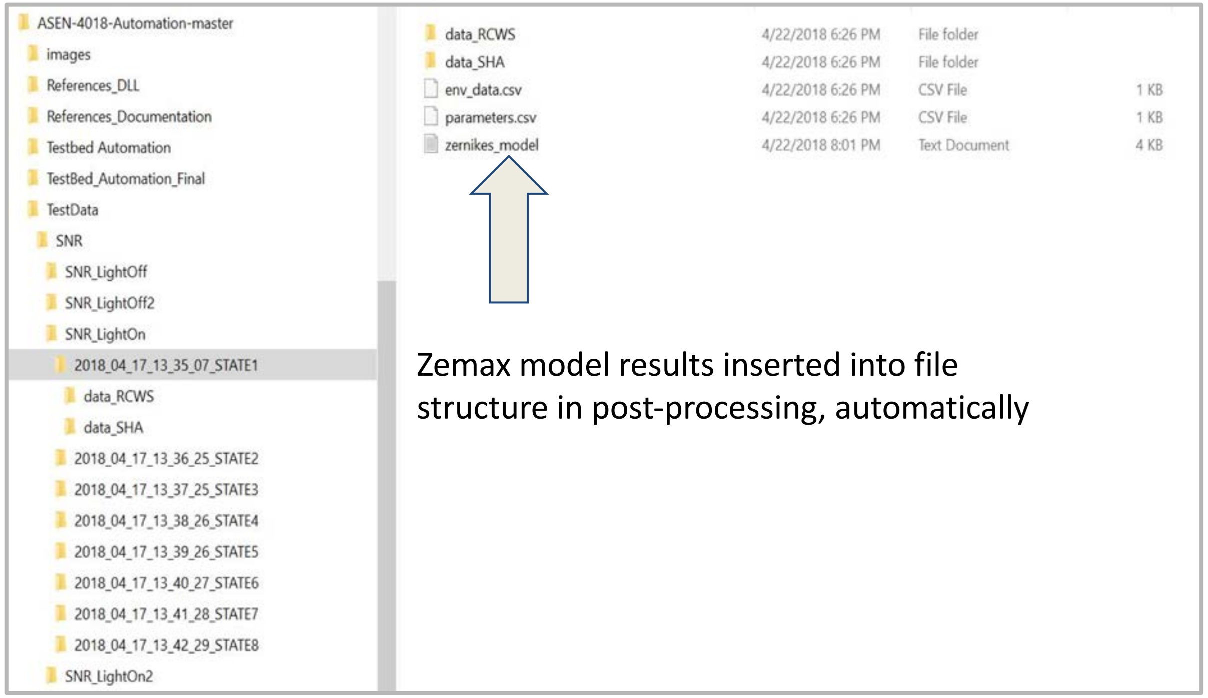
File structure produced by tests

Requirement	Description	Motivation
2.7	Unintentional introduction of wavefront error shall be minimized through design of the test platform.	Testbed automation will reduce the impact of human error.

3.5 – Zemax Model Automation w/ MatLab

```
Surface                        :  Image
Field                          :  0.0000 mm
Wavelength                     :  0.6328 µm
Peak to Valley (to chief)      :      0.00000000 waves
Peak to Valley (to centroid)   :      0.00000000 waves

From integration of the rays:
RMS (to chief)                 :      0.00000000 waves
RMS (to centroid)              :      0.00000000 waves
Variance                       :      0.00000000 waves squared
Strehl Ratio (Est)             :      1.00000000

From integration of the fitted coefficients:
RMS (to chief)                 :      0.00000000 waves
RMS (to centroid)              :      0.00000000 waves
Variance                       :      0.00000000 waves squared
Strehl Ratio (Est)             :      1.00000000

RMS fit error                  :      0.00000000 waves
Maximum fit error              :      0.00000000 waves

Z   1      0.00000000   :        1
Z   2      0.00000000   :         4^(1/2) (p) * COS (A)
Z   3      0.00000000   :         4^(1/2) (p) * SIN (A)
Z   4      0.00000000   :         3^(1/2) (2p^2 - 1)
Z   5      0.00000000   :         6^(1/2) (p^2) * SIN (2A)
Z   6      0.00000000   :         6^(1/2) (p^2) * COS (2A)
Z   7      0.00000000   :         8^(1/2) (3p^3 - 2p) * SIN (A)
Z   8      0.00000000   :         8^(1/2) (3p^3 - 2p) * COS (A)
Z   9      0.00000000   :         8^(1/2) (p^3) * SIN (3A)
Z  10      0.00000000   :         8^(1/2) (p^3) * COS (3A)
Z  11      0.00000000   :         5^(1/2) (6p^4 - 6p^2 + 1)
Z  12      0.00000000   :        10^(1/2) (4p^4 - 3p^2) * COS (2A)
```

The Zernikes text file generated for a particular test

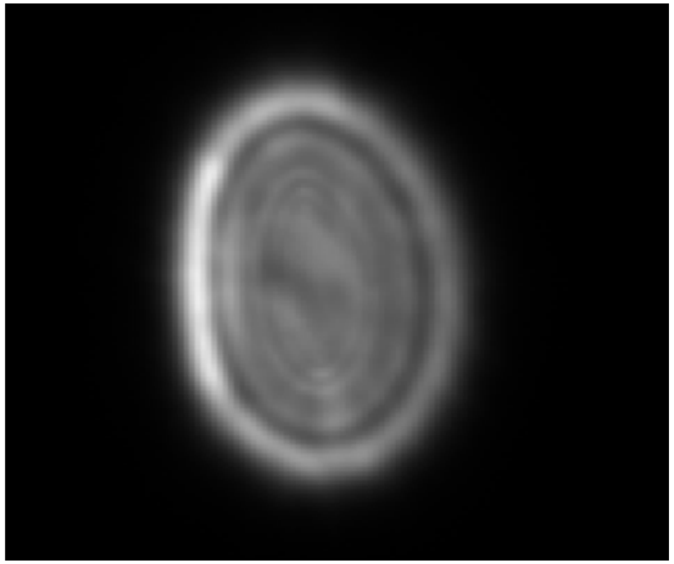


File structure produced after Zemax Automation Run on Test Files

- Uses experiment specification to inform the Zemax model of each particular state
- Records the modelled Zenike amplitudes for a given state
- Uses the tip and tilt data from parameters to run the Zemax simulation

3.6 – Setbacks

- Optical path problems
  - Diffraction patterns from small aperture are not accounted for in Roddier's method
  - Large image displacement for small tip/tilt reduces range of introduceable wavefronts
  - SHA extremely sensitive to location on testbed
    - Certain number of lenslets must be lit to retrieve wavefront measurements
    - In order to increase area covered by light, moved the SHA closer to pellicle in convergent beam
    - Trade-off results in significantly reduced photon flux (lower power) and reduced range to yaw and pitch mirror



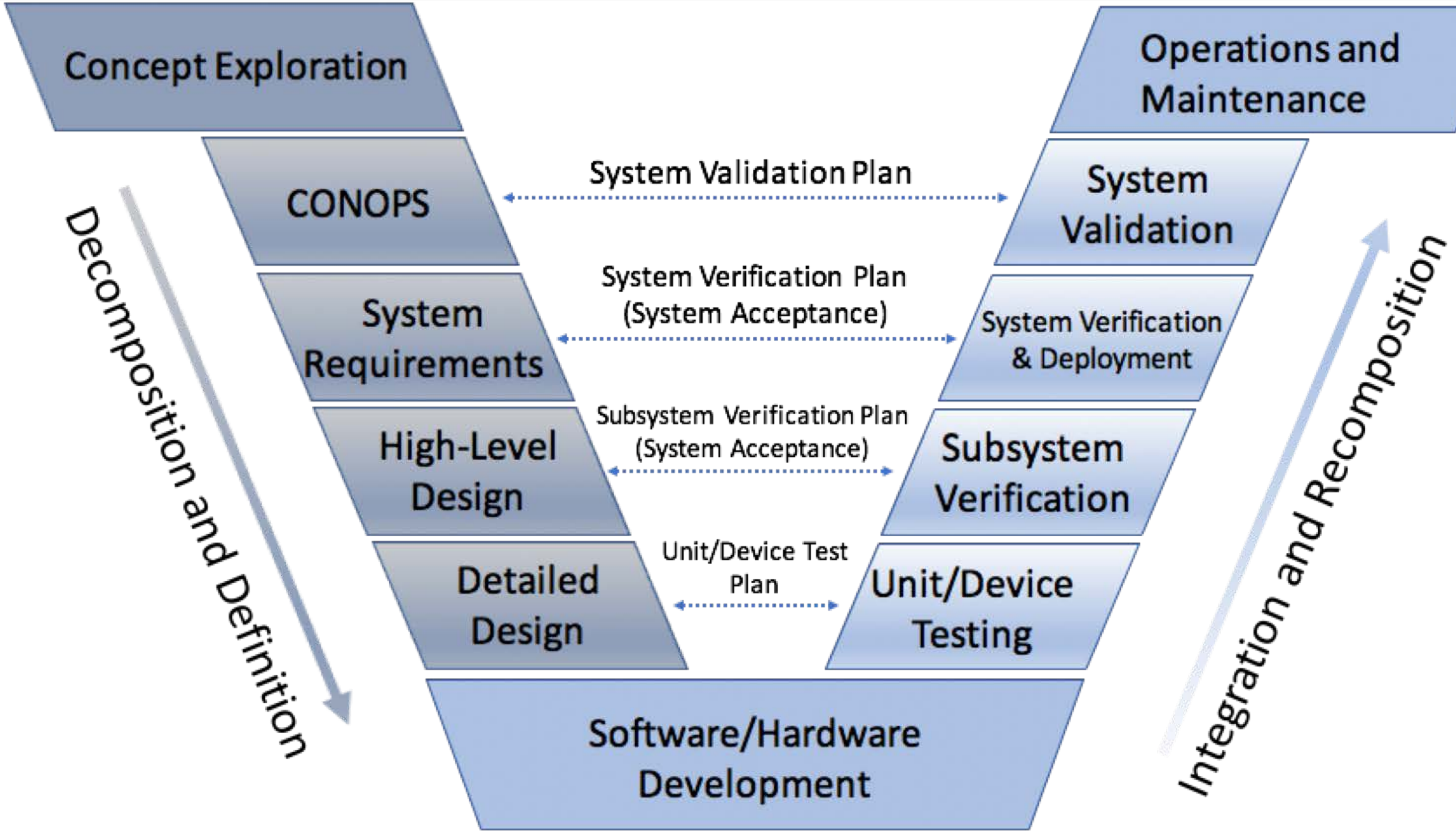
Example of Airy disk patters in images

Setbacks

- Logistical problems
  - Power supplies for test lasers were on campus but not delivered for two weeks
  - Use of optical equipment restricted until moved into lab space, beginning of March
  - Unavailable parts and last-minute replacements
  - Shared lab space occasionally limits access to testing space
  - Software delays due to faulty/poorly documented API interfaces
  - Faulty or no data retrieved through communications
  - Wavefront reconstruction extremely complicated, produces correct ratio of aberrations, but difficult to validate magnitude and higher order terms
  - Some manufacturing delays due to some small parts being forgotten
  - Printed parts delayed because of 3D printer technical issues

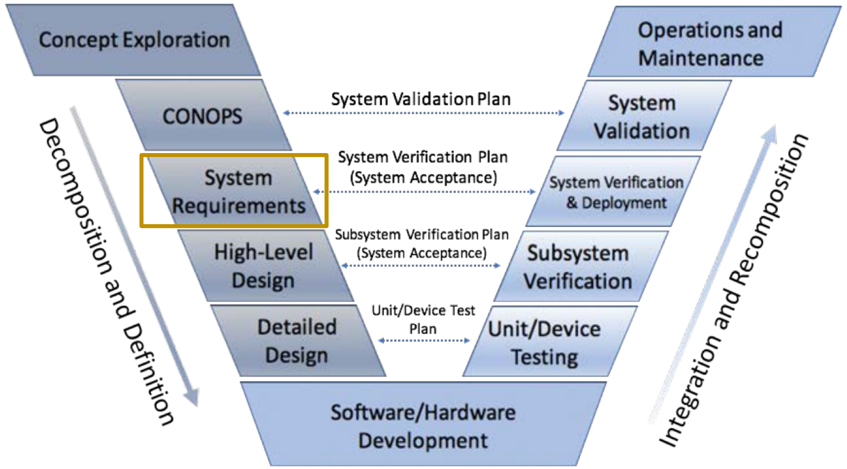
4. SYSTEMS ENGINEERING

4.1 - Systems Engineering V



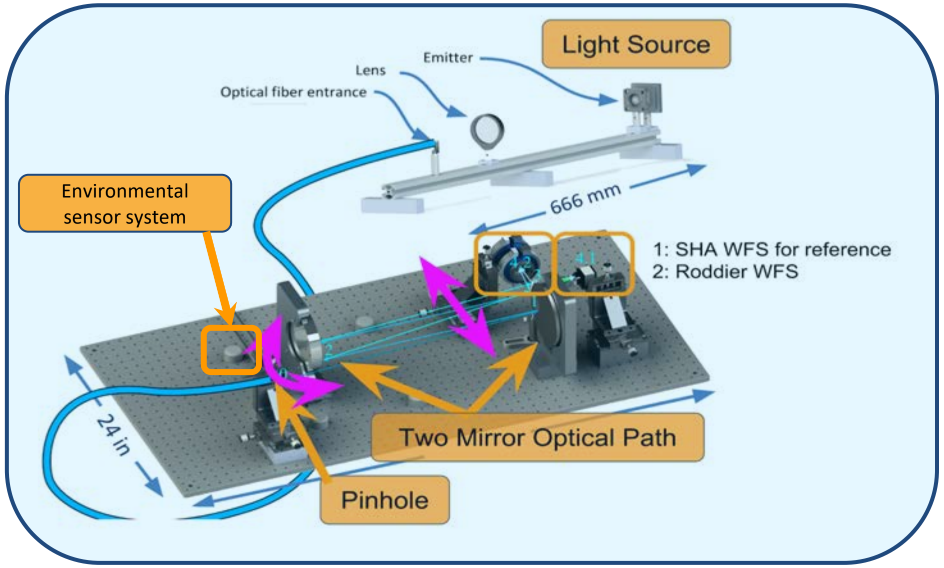
4.2 - Systems Engineering: Requirements

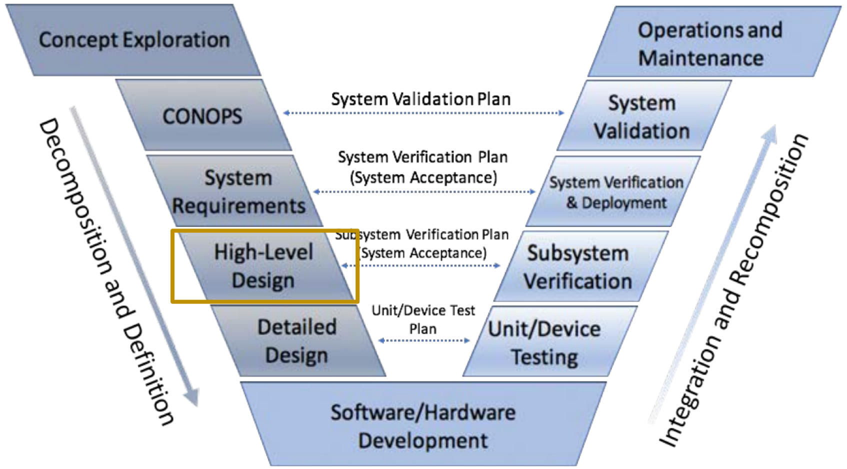
- FR1: Provide Test Setup for both SHA and RCWS Sensors
  - Design an optical front-end to feed known aberrations to the sensors
  - Implement an RCWS as the first test article
  - Use an SHA as the second test article
  - Produce a physical platform to align the optical components
- FR2: Provide Quantitative Assessment of Sensor Performance
- FR3: Test Sensors Under Real Mission Circumstances
  - Maximum received energy tested shall provide an expected shot noise SNR of 100
  - The received energy on the sensors shall be controllable in the range from the full strength to 1/128th that strength in steps halving the energy each time



4.3 - Systems Engineering: High Level Design

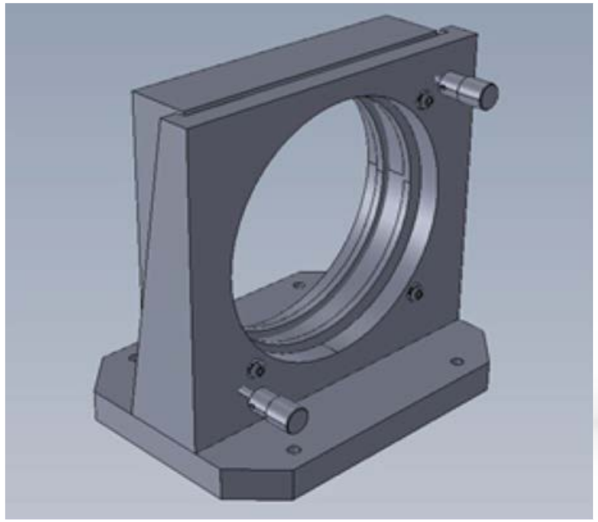
- Limited knowledge of optical engineering provided difficulties again, this time in deriving a baseline design from requirements
- In the end, our customer specified a starting design
- However, many key factors, such as how much to tip/tilt the mirrors, and how far the RCWS needed to traverse, needed to still be determined

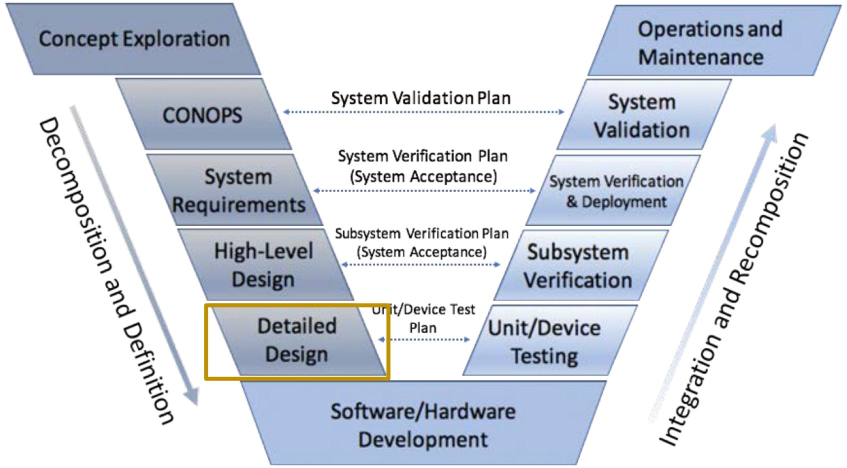




4.4 - Systems Engineering: Key Trades

- Source:
  - Purchase or build
  - LED, Laser, Halogen
- RCWS
  - Range vs resolution of linear stage
- Post-Source
  - How to test both sensors - one at a time or simultaneously
  - How to perform beam-splitting (pellicle vs others)
- Which env. data to care about
  - Magnetic, rotational
- Mirror Mounts:
  - Mirror specific mounts or custom manufactured mount

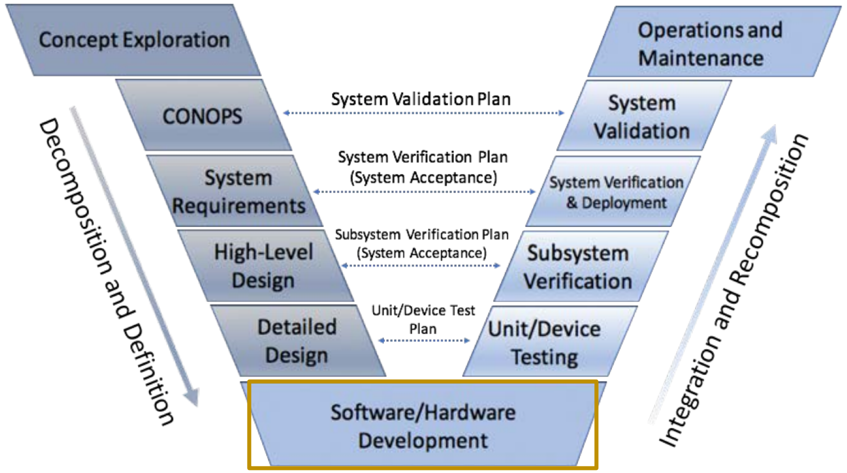




4.5 - Systems Engineering: Software/Hardware Development

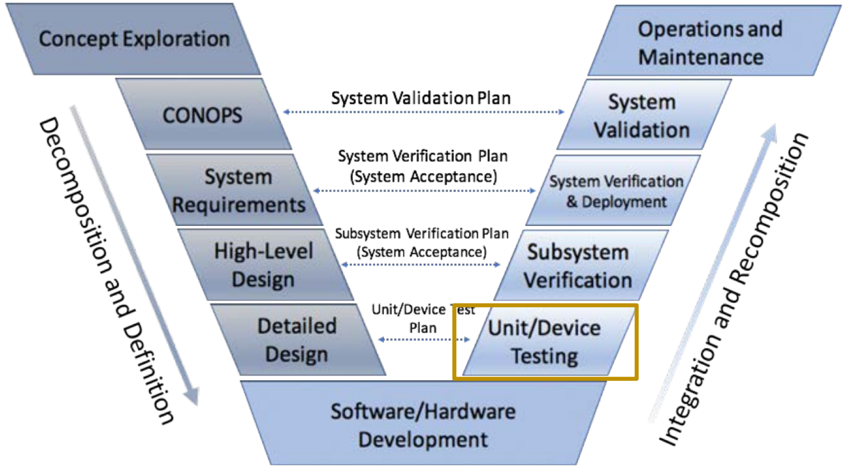
- What Was Done:
  - Machined mirror mounts, pellicle mount, and mounting adapters
  - Manufactured custom light source for introduction of artificial star
  - Developed APIs to control the system automatically
  - Produced custom PCBs and circuits for the environmental sensors

- Issues Encountered:
  - Forgot to add pinhole mount in hardware model
  - LED planned for use in light source was no longer available
  - Unfamiliarity and lack of resources with APIs made their development take longer than expected



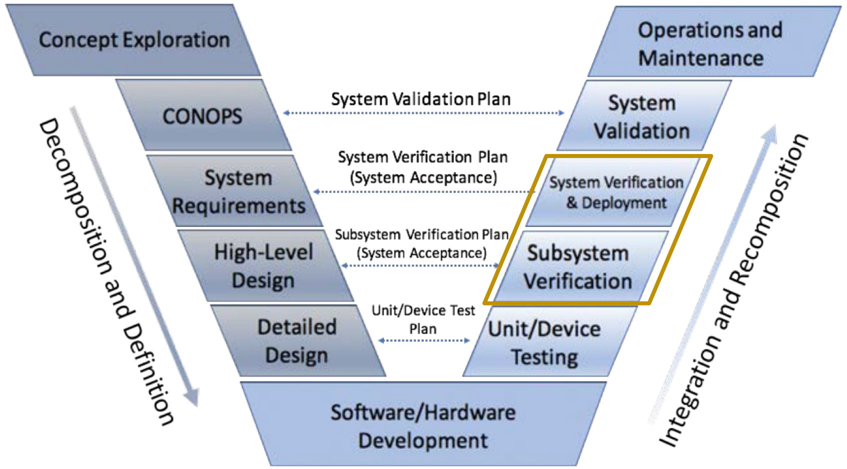
4.6 - Systems Engineering: Unit/Device Testing

- What Was Done:
  - Tested functionality of motor stages and controllers
  - Tested functionality of SHA
  - Tested functionality of RCWS camera
  - Image source components operated correctly
- Issues Encountered:
  - The SHA was able to be operated, but there was no way to determine if the results it produced were correct or not



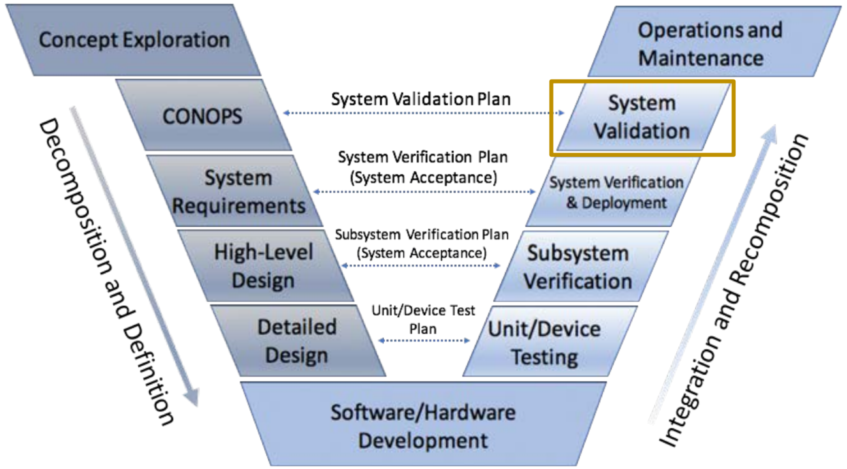
4.7 - Systems Engineering: Subsystem Verification & Deployment

- What Was Done:
  - Entire image source came together and worked correctly
  - Tip/Tilt Platform Resolution
  - Linear Traverse Resolution
  - SNR Measurement
- Issues Encountered:
  - Significant hysteresis with tip/tilt platform
  - Difficulty in aligning the system



4.8 – Systems Engineering: System Validation

- What Was Done:
  - Still in process of completing data collection and characterization of wavefront sensors
- Issues Encountered:
  - Airy disks from small aperture (not part of TIE)
  - Large translation for small tip/tilt reduces range of introduceable wavefronts
  - SHA extremely sensitive to location on testbed
  - Wavefront reconstruction extremely complicated



4.9 - Assessed Risk

- Full FMEA Analysis included in the backup slides
- Major Risks Analyzed
  - Optics and Optomechanics
    - Optics Misaligned
    - Optics Damaged/Dirty
    - Pellicle Beamsplitter Transmission/Reflection Issues
  - Shroud
    - Light pollution inside the test shroud
  - Sensors
    - Errors with APIs controlling the SHA and RCWS
    - Sensors not receiving enough light
- Risk Mitigation Utilized in Final Project
  - Developed optics handling procedures to prevent damage to optics
  - Developed alignment procedures
  - Taped over any lights inside the shroud
  - Shroud built with frame that is mounted on table to reduce gaps between shroud and table
  - Tested with external lights off to minimize chance of external light entering shroud

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Optics/ Optomechanics	Optics Misaligned	Image doesn't appear on sensors	10	Pellicle mounted in wrong spot	8	Check sensors in live feed mode to see when image is/is not visible	4	320
				Pinhole and fiber misaligned	6	Adjustable mount to allow for positioning the fiber in line with the pinhole	5	300
				Cameras not mounted at correct height	4	Laser level and 3 axis Linear stage to ensure correct height	4	160
		Unknown initial wavefront error	5	Mirror axis not parallel	8	Guess and check. Start with mirrors flat on mount and slowly adjust to correct angles while watching image on SHA sensor	7	280
				Pinhole not at focal point of M1	8	Laser level to set height, align with bolt hole pattern for horizontal position	8	320

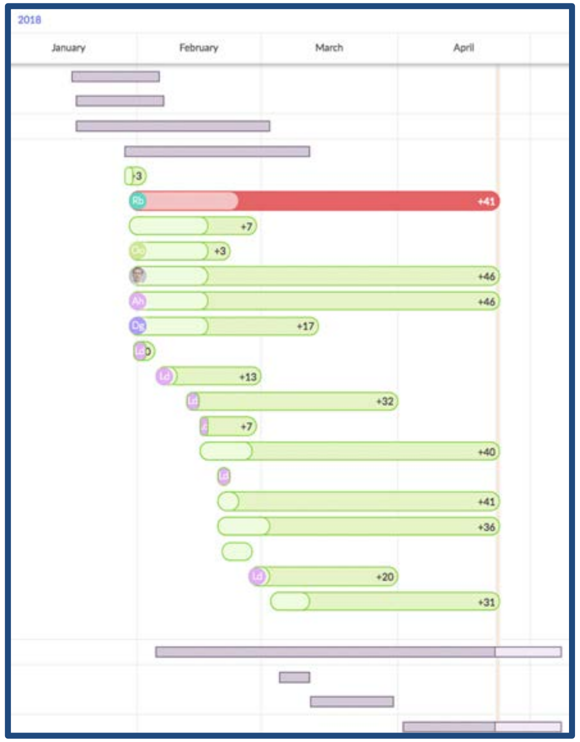
4.10 - Lessons Learned

- It is necessary to have flexible design solutions throughout the entire project
  - Critical design features were realized to need correction in both December and early spring; making it necessary to evaluate where the project was at and then determine the next steps forward
- Overall project success is an iterative process
  - It was expected that all of our requirements would be met from the final design made last semester; however, not all problems encountered in the project could be predicted, making it necessary to redefine the requirements or redefine the design aspects of the project based on lessons learned. If a redesign still did not work, it would then become necessary to keep restarting the design process over again until results were produced that met all of the original requirements
- Success of the ICD (Interface Control Document)
  - A data format specification plan was created early in the spring semester, providing flawless access to all of our data during post-processing

5. PROJECT MANAGEMENT

5.1 - PM Approach

- Tools
  - Used Slack, great for communication and knowledge sharing
  - Redbooth used for task planning/tracking, not as accepted as Slack.
- Team Strategies
  - Knowledge-sharing improved interface between subsystems
  - Flexibility in responsibilities was used when needed to fill coverage gaps, however it also caused additional stress on the team
- Lessons Learned
  - Need to acknowledge and address technical and interpersonal challenges openly
  - As a leader it is important to take a step away from the details of technical work in order to guide the overall project and demonstrate trust in peers



Redbooth GANTT/KanBan

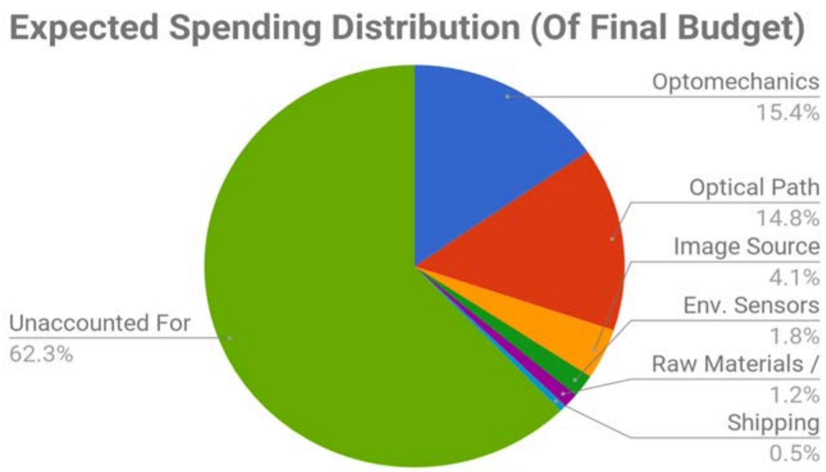
5.2 - Budget:

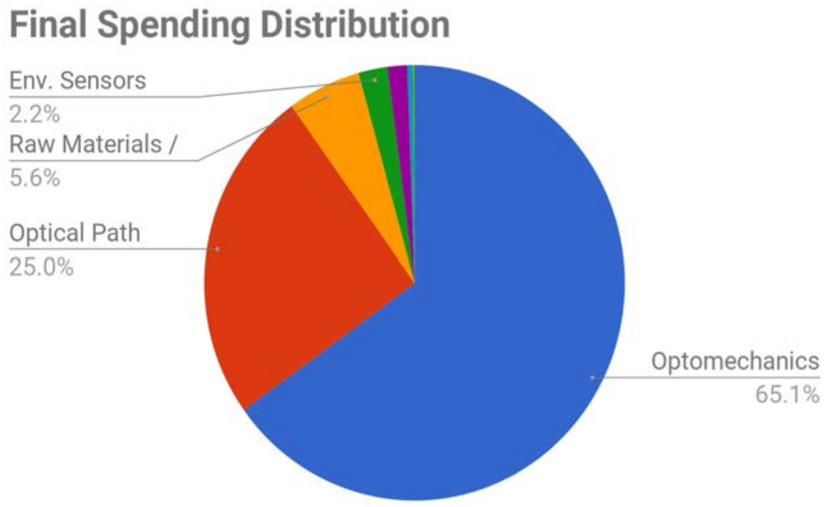
Total spent: $ 11,724.15

Foreseen spending: $ 9,702.86

Unforeseen spending: $ 2,021.29

- Planned for budget of $5,000.00, reduced costs by building image source and planning to build manual alignment stages
- Received additional $8,379.15 funding combined from EEF and additional loaned equipment from SwRI.
- Allowed purchase of COTS alignment stages with far superior precision, aided team in integration + testing
- $1,655.00 margin remaining at end of project - kept in order to replace mirrors, stages, or other critical hardware
- No equipment required replacement due to careful testing procedures
- Unforeseen spending includes shipping, class materials, and additional test equipment, particularly lasers and laser safety gear



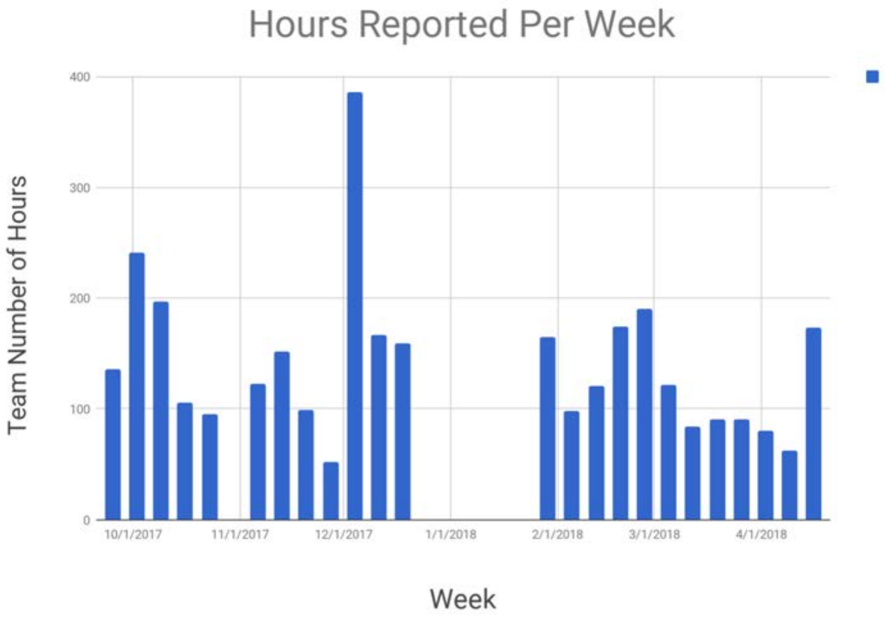


5.3 Effort Expended

- Mean reported: 135 hours per week
- Standard deviation: 74 hours per week
- Large spikes indicate combined work on normal duties and project reports, followed by relaxation and focus on external responsibilities
- Toward end of semester hour reporting becomes unreliable

Total Labor cost: $105,241
Overhead rate: 200%
Parts cost: $11,724

Total cost in industry: $222,205



Thank you for listening!

QUESTIONS?

BACKUP SLIDES

Environmental Sensor Testing

- Received junk data from sensors in testing
- Suspected long wires as the culprit
- Verified that a given sensor worked with small test wire but not with most of the long wires
- Investigated signals on either end of the wire to look for degradation
- Signals at either end appear identical, so other factors must be at play

Budget Details: Summary

	By Purpose		
	Source/Sink	USD ($)	Percent of Total Funding
Funding	Class Budget	-5000	-38.46%
	EEF	-3000	-23.08%
	NASA Glenn	-5000	-38.46%
Spending Breakdown	Optical Path	1729.81	13.31%
	Optomechanics	1804.17	13.88%
	Image Detectors	0	0.00%
	Image Source	479.25	3.69%
	Env. Sensors	214.86	1.65%
	Raw Materials / Misc.	135.99	1.05%
	Shipping	60.65	0.47%
Margin	Margin	-8575.27	-65.96%
Total	Grand Total	4424.73	34.04%

Planned Spending by Subsystem

	By Funding Source		
	Source/Sink	USD ($)	Percent of Total Funding
Funding	Class Budget	-5000	-37.37%
	EEF	-3000	-22.42%
	NASA Glenn	-5379.15	-40.21%
Expected Spending:	Class + EEF	$ 5,087.57	63.59%
	SwRI/NASA Glenn	$ 5,379.15	100.00%
Funds Spent	Class + EEF	$ 6,345.00	79.31%
	SwRI/NASA Glenn	$ 5,379.15	100.00%

Final Spending by Funding Source

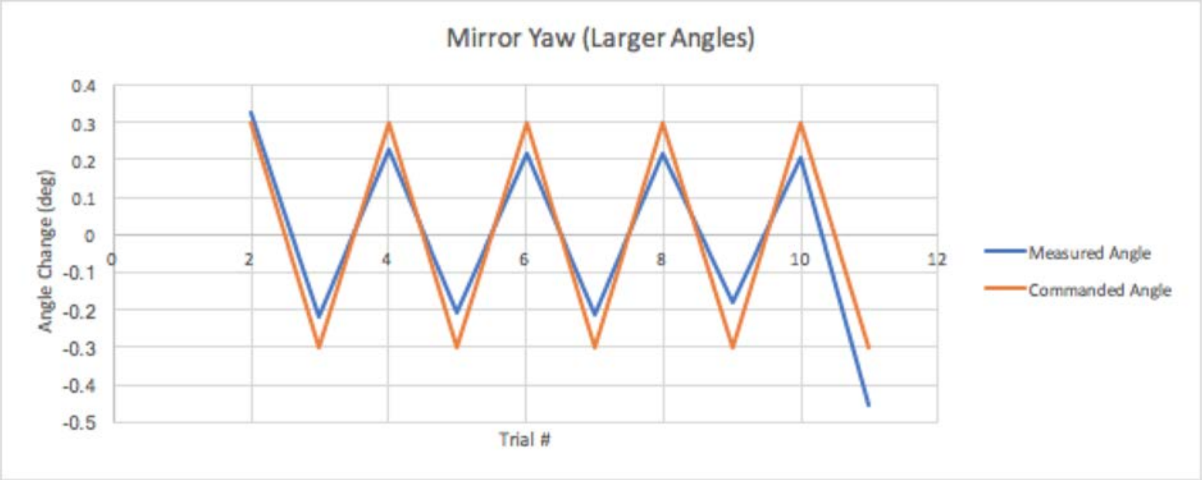
Budget Detail: Bill of Materials

Project ID	Name	Order Number	Ordered	Received	Purpose	Manufacturer	Manufacturer ID	Source	Source ID	Quantity	Cost Each ($)	Discount Each (%)	Subtotal ($)
									Optical Path				
O-1	Parabolic Mirror	P2	1.16.18	1.19.18		Edmund Optics	32-069-533	Edmund Optics	32-069-533	2	675	0	1350
O-2	Pellicle Beamsplitter	P2	1.16.18	1.19.18		Edmund Optics	39-481	Edmund Optics	39-481	2	170	0	340
O-3	Clamp	P6	1.25.18	1.31.18	Clamping to table	ThorLabs	CF125	ThorLabs	CF125	1	8.95	0	8.95
O-4	Post holder	P6	1.25.18	1.31.18	Holding posts	ThorLabs	PH3E	ThorLabs	PH3E	1	24.99	0	24.99
O-5	Post	P6	1.25.18	1.31.18	Post	ThorLabs	TR4	ThorLabs	TR4	1	5.87	0	5.87
									Optomechanics				
T-1	PY004Z8	S0	1.24.18	1.30.18	M2 pitch and yaw platform	ThorLabs	PY004Z8	ThorLabs	PY004Z8	1	2113.44	-100	0
T-2	PT1-Z8	S0	1.24.18	1.30.18	RCWS translation stage	ThorLabs	PT1-Z8	ThorLabs	PT1-Z8	1	840.48	-100	0
T-3	KCH301	S0	1.24.28	1.30.18	Power supply for 3 motors	ThorLabs	KCH301	ThorLabs	KCH301	1	494.7	-100	0
T-4	KDC101	S0	1.24.28	2.5.18	Motor controller	ThorLabs	KDC101	ThorLabs	KDC101	3	638.52	-100	0
T-5	PT1-B	P6	1.25.18	1.31.18	Alignment traverse stage	ThorLabs	PT1-B	ThorLabs	PT1-B	7	215.22	0	1506.54
T-6	KM100 WFS	P6	1.25.18	1.31.18	SHA tip/tilt	ThorLabs	KM100 WFS	ThorLabs	KM100 WFS	1	83.39	0	83.39
T-7	PY003	P6	1.25.18	1.31.18	RCWS tip/tilt	ThorLabs	PY003	ThorLabs	PY003	1	214.24	0	214.24
									Image Detectors				
D-1	ASI120MM-S		Have	Possession	CMOS Detector	ZWS	ASI120S	Eliot	ASI120S	1	199	-100	0
D-2	QHY 174M		Have	Possession	CMOS Detector	QHY	QHY 174M	Eliot	QHY 174M	1	939	-100	0
D-3	WFS150-7AR		Have	Possession	SHA	ThorLabs	WFS150-7AR	Eliot	WFS150-7AR	1	4009	-100	0

Budget Detail: Bill of Materials (cont.)

									Image Source				
I-1	LH-XP-100W-6000k	P5	1.24.18	1.30.18	Emitter	AMZNSPCL	LH-XP-100W-600	Amazon	LH-XP-100W-60	1	12.89	0	12.89
I-2	LPV-100-12	P5	1.24.18	1.30.18	Power Supply	Mean Well	LPV-100-12	Amazon	LPV-100-12	1	25.2	0	25.2
I-3	GREE U024V	P5	1.24.18	1.30.18	Boost Converter	GREE	GREE U024V	Amazon	GREE U024V	1	11.69	0	11.69
I-4	Heatsink		2.2.18	2.7.18	Heatsink	Advanced Thermal Slutions Inc.	ATS-54170W-C1-R	DigiKey	ATS1247-ND	1	7.79	0	7.79
I-5	LB1106-A	P6	1.25.18	1.31.18	Biconvex lens	ThorLabs	LB1106-A	ThorLabs	LB1106-A	1	43.1	0	43.1
I-6	P10H	P6	1.25.18	1.31.18	Pinhole	ThorLabs	P10H	ThorLabs	P10H	1	74.5	0	74.5
I-7	FCM32	P6	1.25.18	1.31.18	Fiber Mount	ThorLabs	FCM32/M	ThorLabs	FCM32/M	2	22.64	0	45.28
I-8	ACL25416U-A	P6	1.25.18	1.31.18	Condenser Lens	ThorLabs	ACL25416U-A	ThorLabs	ACL25416U-A	1	27.54	0	27.54
I-9	LMR2	P6	1.25.18	1.31.18	lens mount	ThorLabs	LMR2	ThorLabs	LMR2	1	25.76	0	25.76
I-10	SM1RRC	P6	1.25.18	1.31.18	retaining ring	ThorLabs	SM1RRC	ThorLabs	SM1RRC	1	10.51	0	10.51
I-11	CP02	P6	1.25.18	1.31.18	Cage Plate	ThorLabs	CP02	ThorLabs	CP02	1	16.4	0	16.4
I-12	SM1L05	P6	1.25.18	1.31.18	Lens tube	ThorLabs	SM1L05	ThorLabs	SM1L05	1	12.59	0	12.59
I-13	TR1	P6	1.25.18	1.31.18	Post	Thorlabs	TR1V	Thorlabs	TR1V	2	4.74	0	9.48
I-14	TR075	P6	1.25.18	1.31.18	Post	Thorlabs	TR075V	Thorlabs	TR075V	1	4.74	0	4.74
I-15	TR1.5	P6	1.25.18	1.31.18	Post	Thorlabs	TR1.5V	Thorlabs	TR1.5V	1	4.97	0	4.97
I-16	M105L02S-B	P6	1.25.18	1.31.18	Fiber optic cable	ThorLabs	M105L02S-B	ThorLabs	M105L02S-B	1	131.58	0	131.58
I-17	LMR1	P6	1.25.18	1.31.18	Pinhole mount	ThorLabs	LMR1	ThorLabs	LMR1	1	15.23	0	15.23
									Environmental Sensors				
E-1	Teensy3.6	P3	1.16.18	1.23.18	Microcontroller	PJRC	Teensy3.6	PJRC	Teensy3.6	1	29.25	0	29.25
E-2	ADXL344ACCZ-RL7	P4	1.17.18	1.22.18	Temperature sensor	Analog Devices Inc.	ADXL344ACCZ-RL	Digikey	ADXL344ACCZ -RL7CT-ND	10	3.041	0	30.41
E-3	ADT7320UCPZ-RL7CT	P4	1.17.18	1.22.18	Accelerometer	Analog Devices Inc.	ADT7320UCPZ-RL	Digikey	ADT7320UCPZ-R	10	6.934	0	69.34
E-4	8 Pin Header M	P4	1.17.18	1.22.18	SPI Sensor Connection	Amphenol	20021121-00008C4	DigiKey	609-3694-2-ND	30	0.609	0	18.27
E-5	8 Pin Header F	P4	1.17.18	1.22.18	SPI Sensor Connection	Amphenol	20021311-00008T4	DigiKey	609-3753-ND	30	0.596	0	17.88
E-6	10k Resistors	P4	1.17.18	1.22.18	10k resistors	Vishay Beyschlag	MCT06030C1002FF	DigiKey	MCT0603-10.0K-C	100	0.0596	0	5.96
E-7	0.1uF cap	P4	1.17.18	1.22.18	0.1uF cap	Murata Electronics North America	GRM188R71C104K	DigiKey	490-1532-1-ND	100	0.0316	0	3.16
E-8	Regulator	P4	1.17.18	1.22.18	3.3V Regulator	Exar Corporation	SPX1117M3-L-3-3/T	DigiKey	1016-1848-1-ND	10	0.378	0	3.78
E-9	Male Header	P4	1.17.18	1.22.18	Male Header	Sullins Connector Solutions	PRPC040SAAN-RC	DigiKey	S1011EC-40-ND	10	0.592	0	5.92
E-10	USB	P4	1.17.18	1.22.18	USB Cord	Qualtek	3025010-03	DigiKey	Q853-ND	2	2.51	0	5.02
E-11	Cables	P4	1.17.18	1.22.18	Sensor Cables	Tensility International Corp	30-00510	DigiKey	T1347-5-ND	1	9.99	0	9.99
E-12	Solder Paste	P4	1.17.18	1.22.18	Solder Paste	Chip Quik Inc.	SMD291AX50T3	DigiKey	SMD291AX50T3-	1	12.98	0	12.98

Results - Mirror Yaw Control



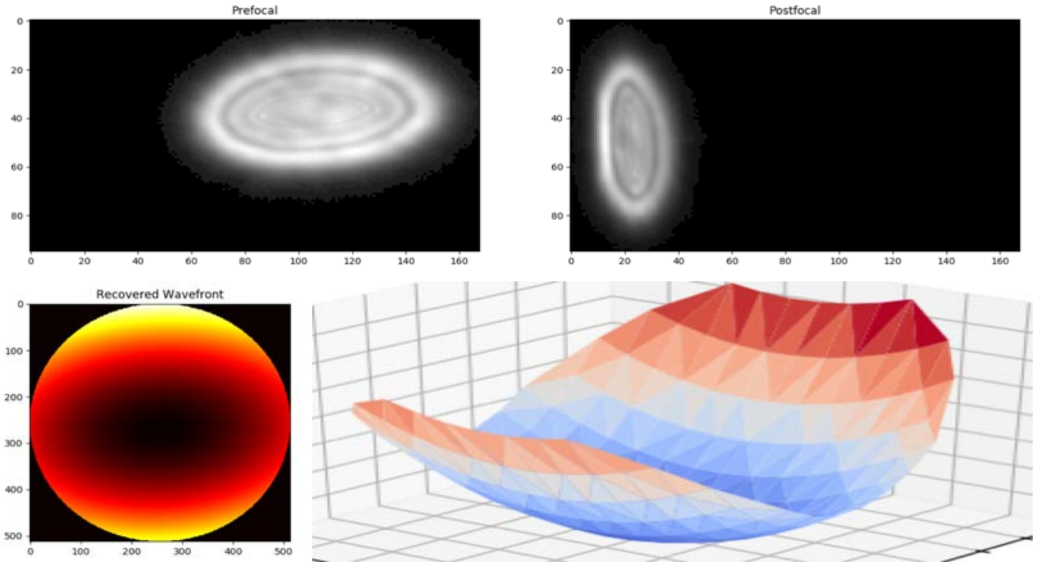
The image moving across the image sensor due to changing tip/tilt of M2.

Performance is better for larger commanded angles.

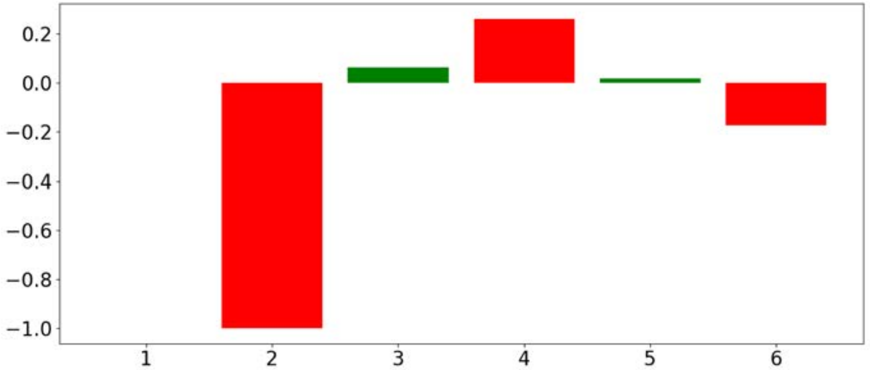
Average Error (deg)	Standard Deviation (deg)
0.0901	0.0313

Requirement	**Description**	**Motivation**
2.2.1	Wavefront error shall be introduced in resolution equal to or exceeding a RMS optical path delay of lambda/50, where lambda is the center wavelength of the image source.	Validating rotational accuracy of pitch/yaw stage.

Wavefront Reconstruction



Relative Zernike Mode Strengths



Performed preliminary wavefront reconstruction from RCWS data as in level 2 success.

Generated correct wavefront shape and relative magnitudes of Zernike amplitudes, but unable to be certain of scale in terms of waves.

Pellicle Characterization

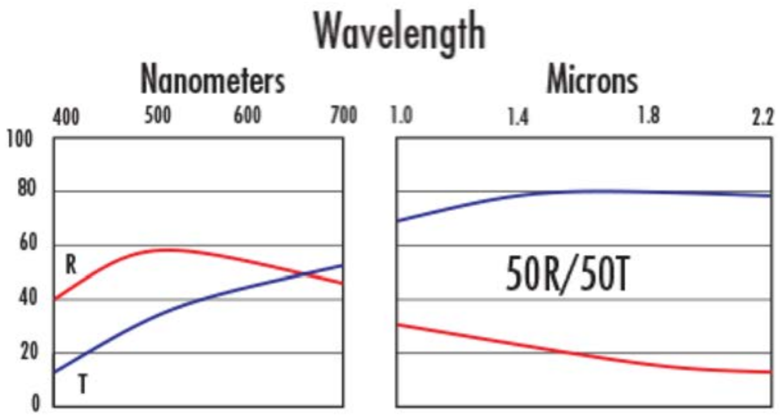
Purpose: Compare the total intensity distribution to validate that the pellicle is ~50/50 reflected/transmitted for the light emitted by the image source.

Required Equipment: CMOS, Image Source, Optical Fiber, Pellicle

Method: Mount the optical fiber, pellicle (at 45deg angle), and CMOS in a line and take imagery in this “through” position. Then mount the CMOS in the “reflected” position located 90deg from original position around the pellicle.

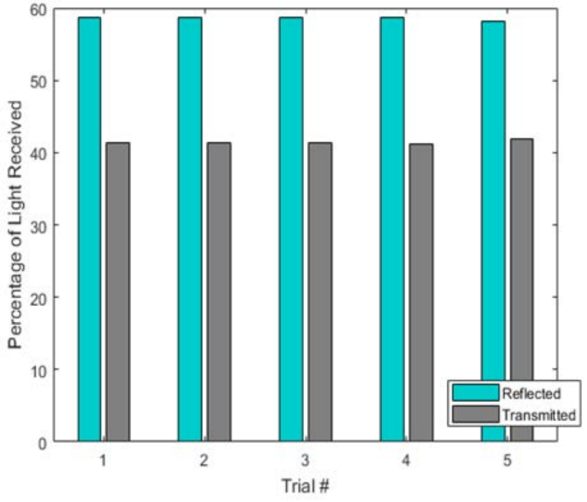
Pellicle Characterization

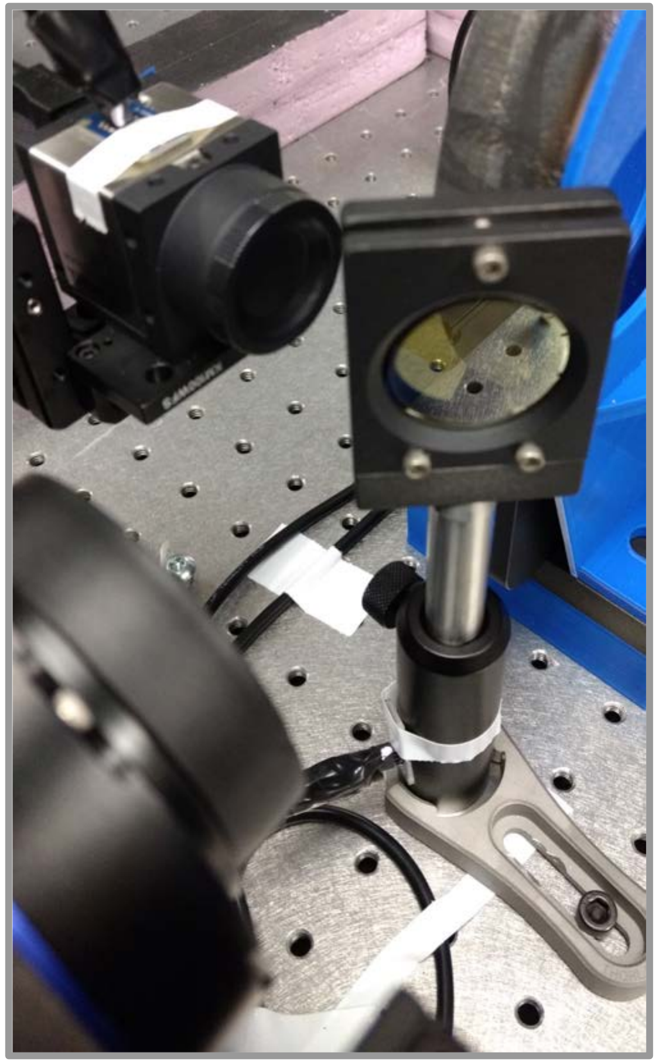
- 50/50 pellicle only applicable at 650 nm
- Determine ratio of reflectance and transmission to compensate SNR for the two sensors in post-processing
- Approximately 60/40 split observed corresponds with expected 550 nm peak of LED
- Confirms Specification from Edmunds



Specification from Edmunds

Test Results





Testbed Alignment

Purpose: To ensure the optics are aligned in order to allow for data collection.

Method: Set up testbed in rough position based on solidworks model

Move set screws on back of mirror mount to align optics and put the image on the SHA sensor (no pellicle)

Adjust angle of SHA to remove tilt/tip aberrations

Add pellicle and set angle such that the image lies on both the SHA and RCWS sensors

Results: Satisfies FR1.1 - FR1.4

Assessed Risk: FMEA

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Optics/ Optomechanics	Optics Misaligned	Image doesn't appear on sensors	10	Pellicle mounted in wrong spot	8	Check sensors in live feed mode to see when image is/is not visible	4	320
				Pinhole and fiber misaligned	6	Adjustable mount to allow for positioning the fiber in line with the pinhole	5	300
				Cameras not mounted at correct height	4	Laser level and 3 axis Linear stage to ensure correct height	4	160
		Unknown initial wavefront error	5	Mirror axis not parallel	8	Guess and check. Start with mirrors flat on mount and slowly adjust to correct angles while watching image on SHA sensor	7	280
				Pinhole not at focal point of M1	8	Laser level to set height, align with bolt hole pattern for horizontal position	8	320

Assessed Risk: FMEA (cont.)

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Optics/ Optomechanics	Optics Damaged	Cannot Produce Images with both sensors	10	Broken/Cracked Mirrors	6	Training in handling optics, minimizing the amount of time handling optics	3	180
				Torn Pellicle	8	Training in handling optics, minimizing the amount of time handling optics	4	320
				Broken Camera	4	Leaving cameras mounted to minimize handling time and capping the cameras whenever they are not in use	7	280
		Unexpected Wavefront error Introduced	5	Dirty Mirrors	8	Training in handling optics, minimizing the amount of time handling optics	6	240
				Dirty Pellicle	8	Training in handling optics, minimizing the amount of time handling optics	6	240

Assessed Risk: FMEA (cont.)

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Optics/ Optomechanics	Motorized Tilt Tip platform doenst function as desired	Cannot adjust tilt/tip	7	Motor controller communication problems	3	Using off the shelf software provided by stage manufacturer	4	84
				Movement impared by bolts mounting components to stage	3	Using shortest bolts possible for mounting components effectivly	3	63
				Other components on testbed hinder movement	3	Stage selected based on design that provided buffer around each component in the testbed (modeled in SolidWorks)	1	21
		Historesis in positioning	4	Motors not accurate enough	1	Using motors designed for optics with minimal backlash	5	20
				Mirror and mount too heavy for stage	8	Mounts and mirrors as specified from design	5	160

Assessed Risk: FMEA (cont.)

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Optics/ Optomechanics	Pellicle	Doesn't split light evenly between reflection and transmission	6	Reflective coating doesn't transmit and reflect every wavelength the same	10	N/A	3	180
		Sensor on reflection side of pellicle obtains different tilt error	6	Physics	10	N/A	1	60
	Mirror mounts design	Mirror mount blocks optical path	10	Mount Completely surrounds edge of mirror	1	Custom mounts desinged to leave one side of mirror unobstructed	1	10
		Mirror angle not correct	6	Mount doesn't allow angular adjustment	1	Custom mounts desinged to constrain all degrees of freedom with adjustability on the mirror angle	4	24
				Mirror angle not properly set	8	Alignment procedures	4	192

Assessed Risk: FMEA (cont.)

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Shroud	Light Polution	Too low of SNR	5	Gaps in shroud	3	Constructed a frame to mount on table to minimize the gap by the table, taped seams in the shroud	8	120
				Lights on components inside shroud	3	Tapeing over lights inside shroud	8	120
Sensors	API controlling the cameras	Not outputting the required data	6	Camera not designed to provide that data	5	Researched cameras to make sure they provide the needed information	2	60
				API doesn't output that data	6	Required infromation was provided to the developers before they wrote APIs	3	108

Assessed Risk: FMEA (cont.)

Process Step	Potential Failure Mode	Potential Effects	SEV	Potential Cause	OCC	Current Controls	DET	RPN
Sensors	Sensors not receiving enough light	Cannot capture data	8	Source does not produce enough light	5	N/A	7	280
				Image too small on sensor	7	N/A	7	392
		Not enough data to extract wavefront error	8	Source does not produce enough light	5	N/A	7	280
				Image too small on sensor	7	N/A	7	392
	RCWS Analysis Algorithm	Doesn't calculate the wavefront properly	7	Incorrect algorithm	4	Algorithm based on paper by Roddier	9	252
				RCWS travel distance not ideal to show wavefront	5	Multiple testst to determine the optimal travel distance	7	245