Apparatus for Wavefront Error Sensor Measurement:
CDR

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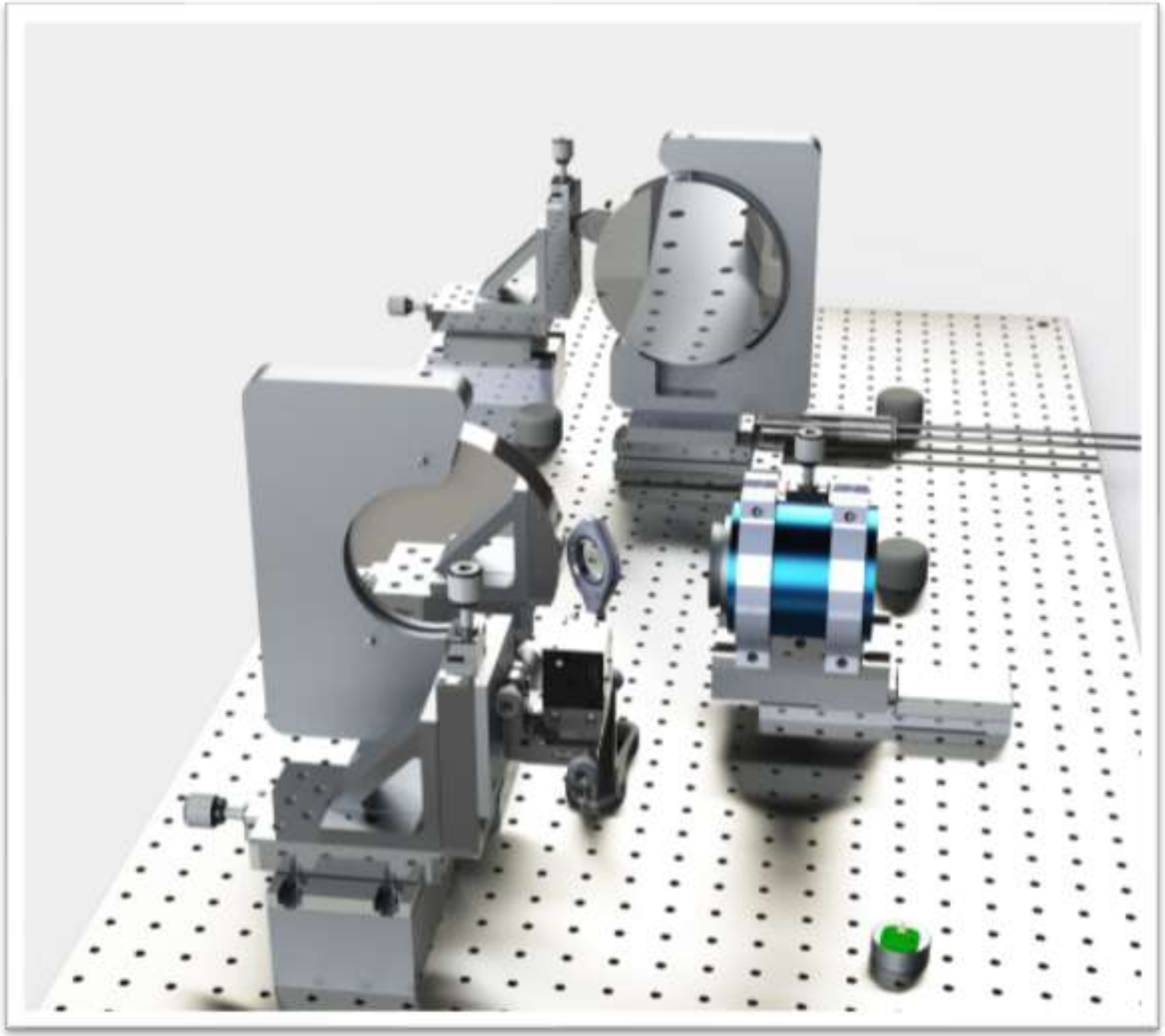
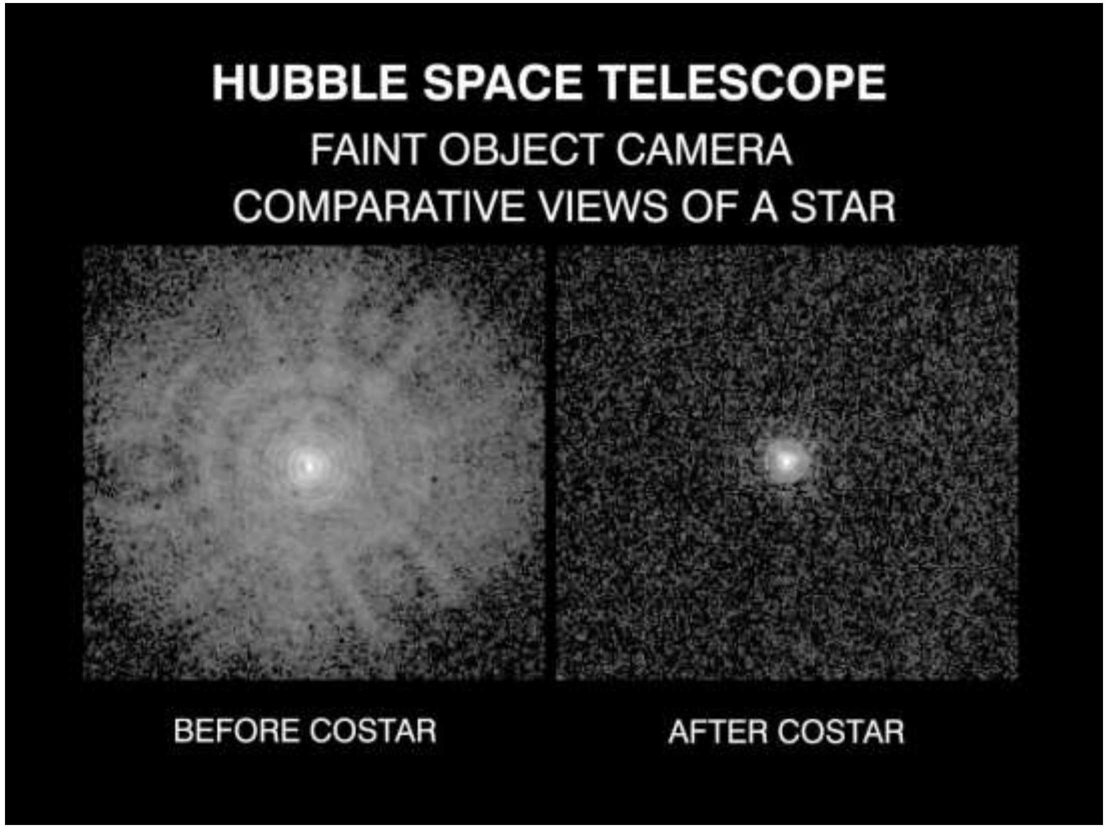
Southwest Research Institute
&
NASA Glenn Research Center

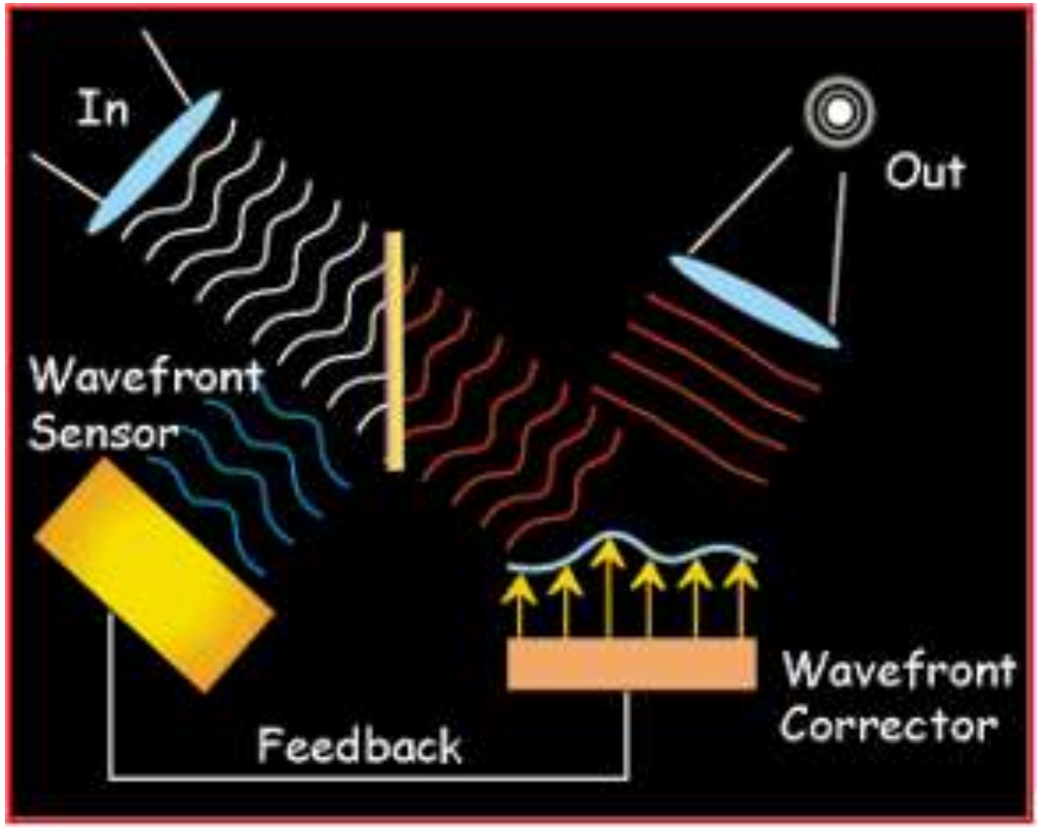


1.0 PROJECT PURPOSE AND OBJECTIVES

1.1 - Introduction



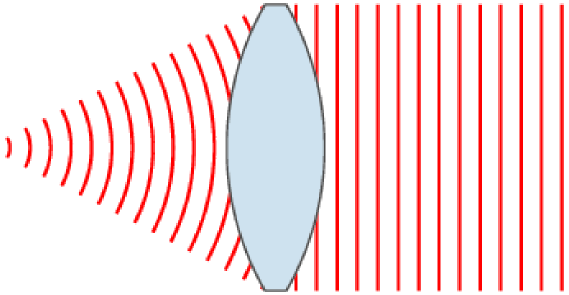
Optical systems are susceptible to small errors imparted from the environment and the tolerances in the system



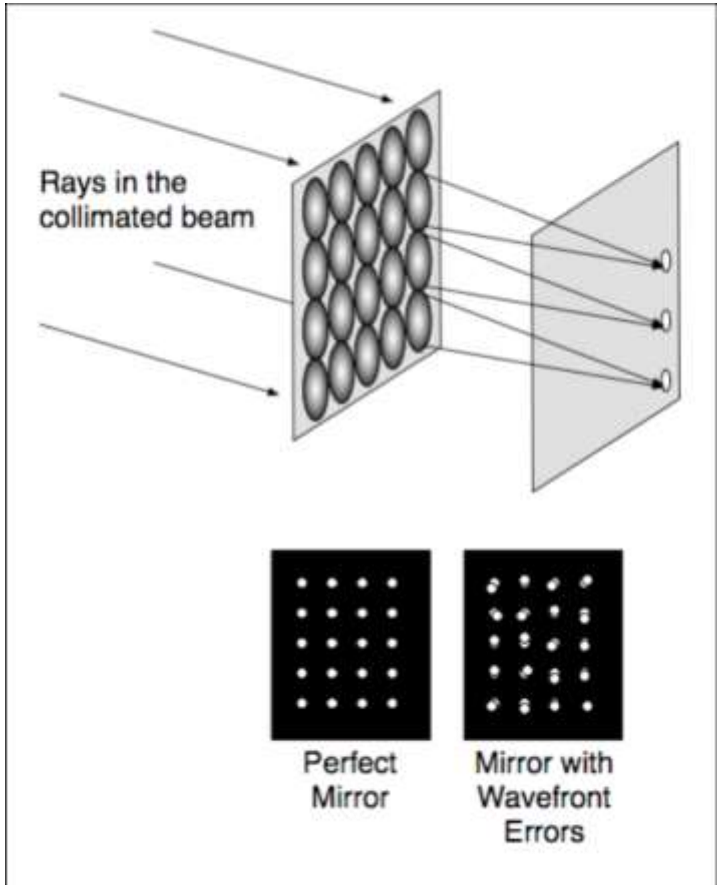
Active optics (AO) uses wavefront measurements to correct optical systems

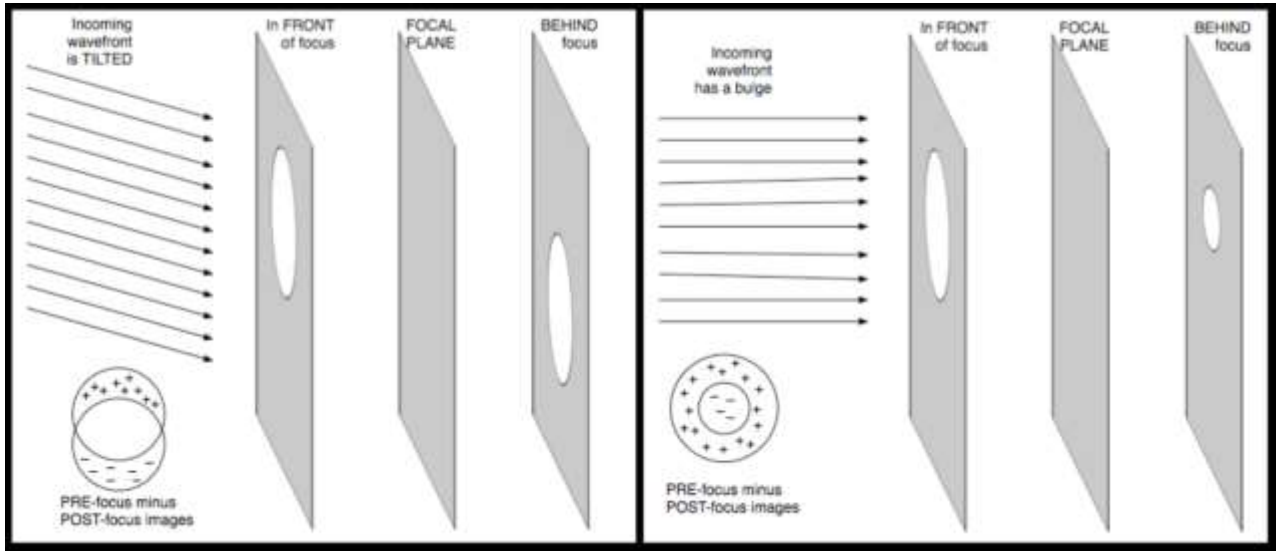
1.1 - Wavefront Sensors

- A wavefront is a continuous constant-phase surface of light from one source
- At the focal point of the system, deviation from spherical wavefront is wavefront error
- Shack-Hartmann Array (SHA) vs.
  Roddier Curvature Wavefront Sensor (RCWS)



Shack-Hartmann Method
(Below)





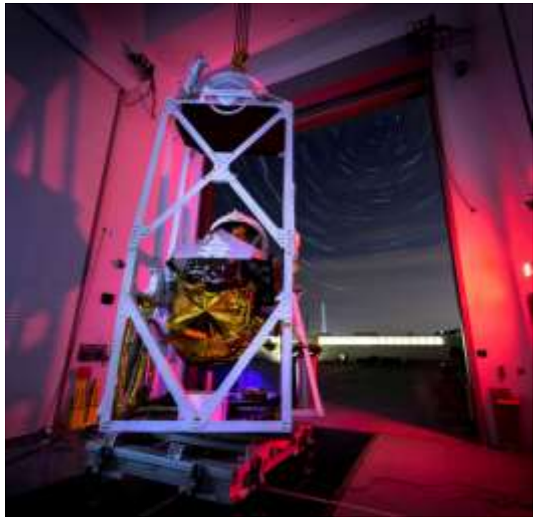
Roddier Method (Left)

1.1 - Motivation

Potential benefits of RCWS:

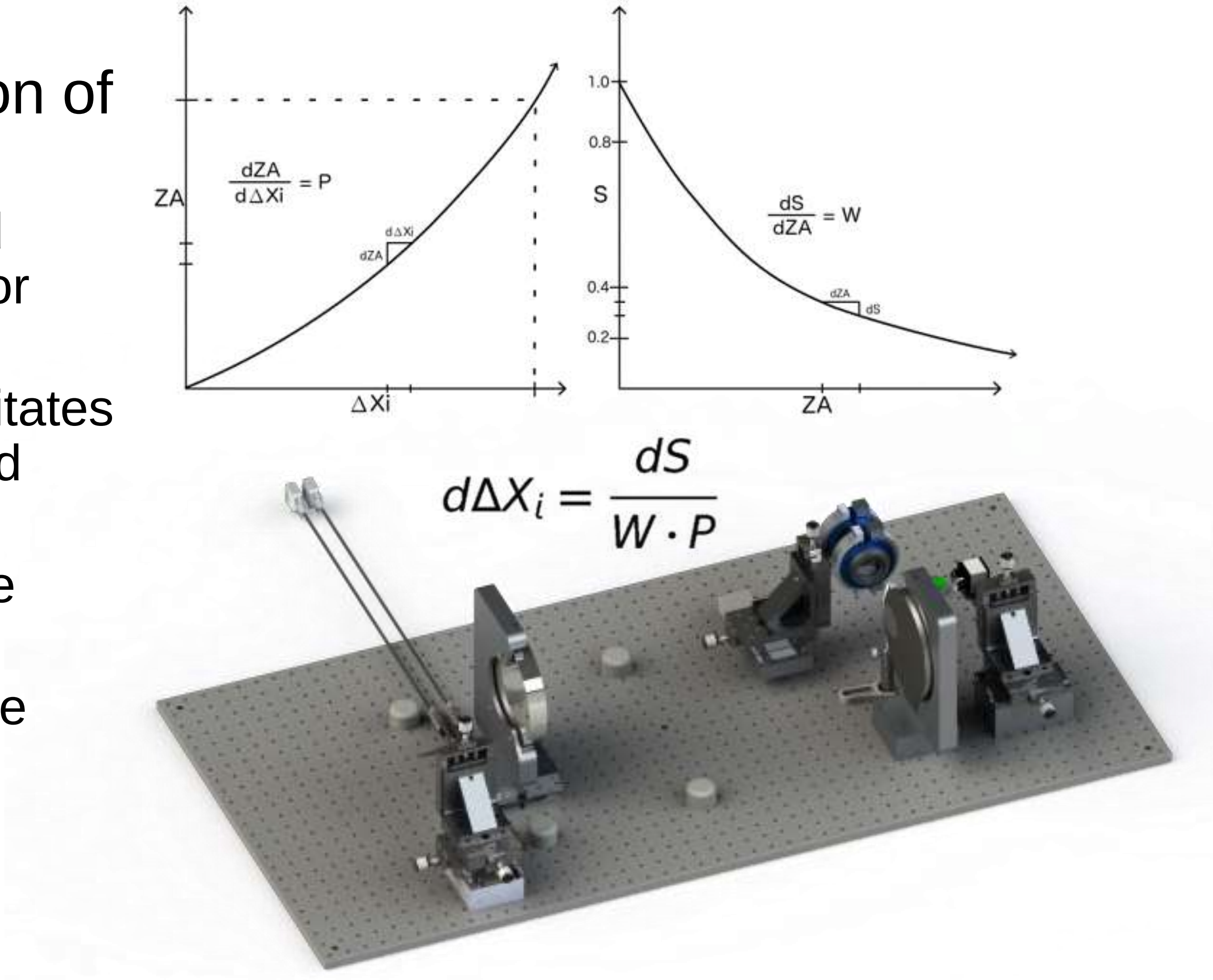
- Simplicity in design:
  - Optics systems generally have a system for changing the focal length
  - No need to access the pupil
  - Can use the main image detector

- The RCWS method has the potential to perform equally or even better than the currently used methods on aerial platforms as long as it meets performance expectations.
- Future missions could choose SHA or RCWS systems based on performance data generated by a comparison



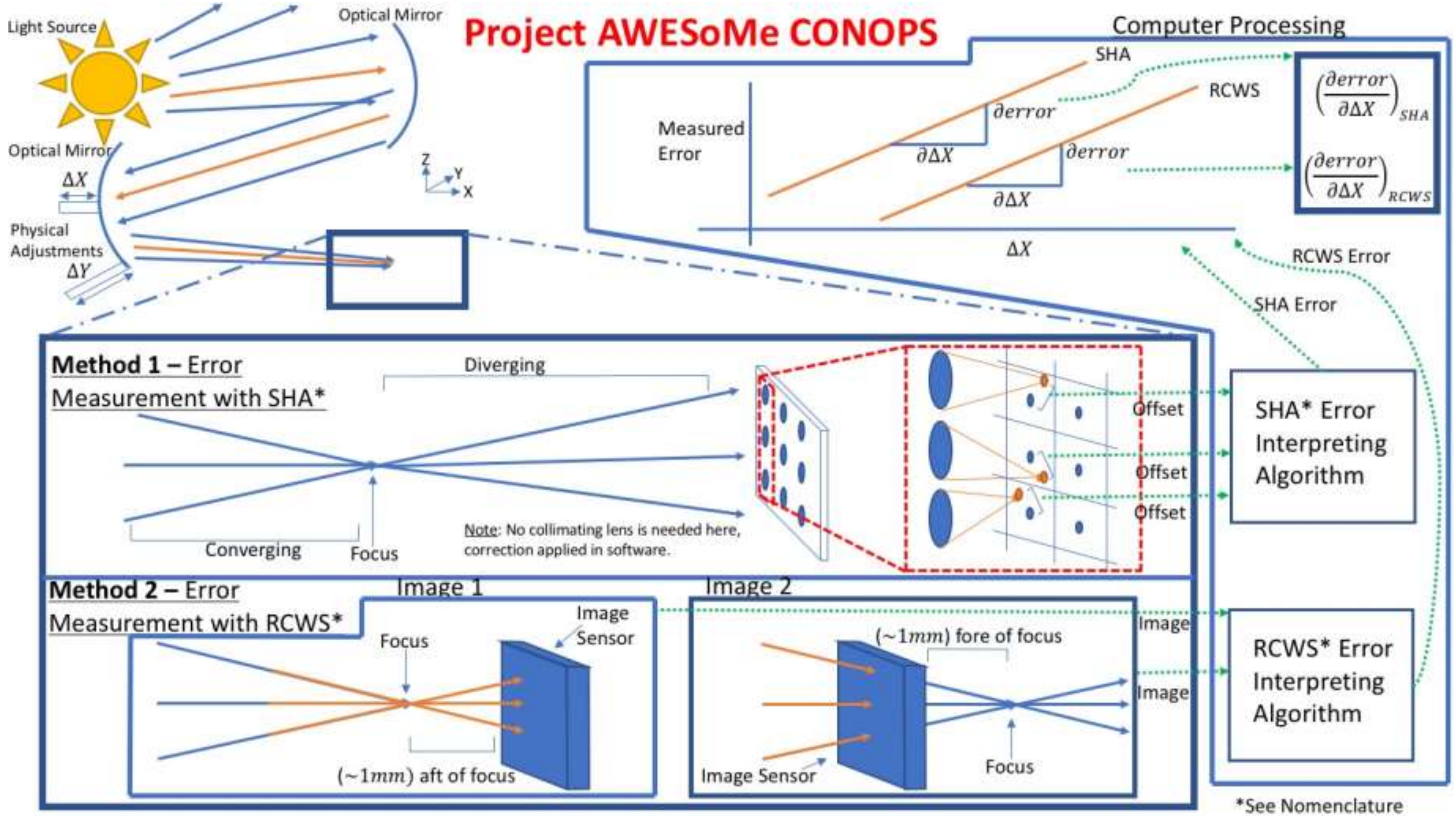
1.2 - Objectives

- Quantitatively compare the SHA and RCWS wavefront sensors as a function of source intensity
  - Measure the rate of response of detected Zernike polynomials to introduced error for both sensors
  - Design and build a test platform that facilitates data collection with required precision and accuracy
  - Develop a prototype Roddier sensor to be used in the comparison
  - Use forward-predictive models to drive the design and validate results
- Present preliminary results



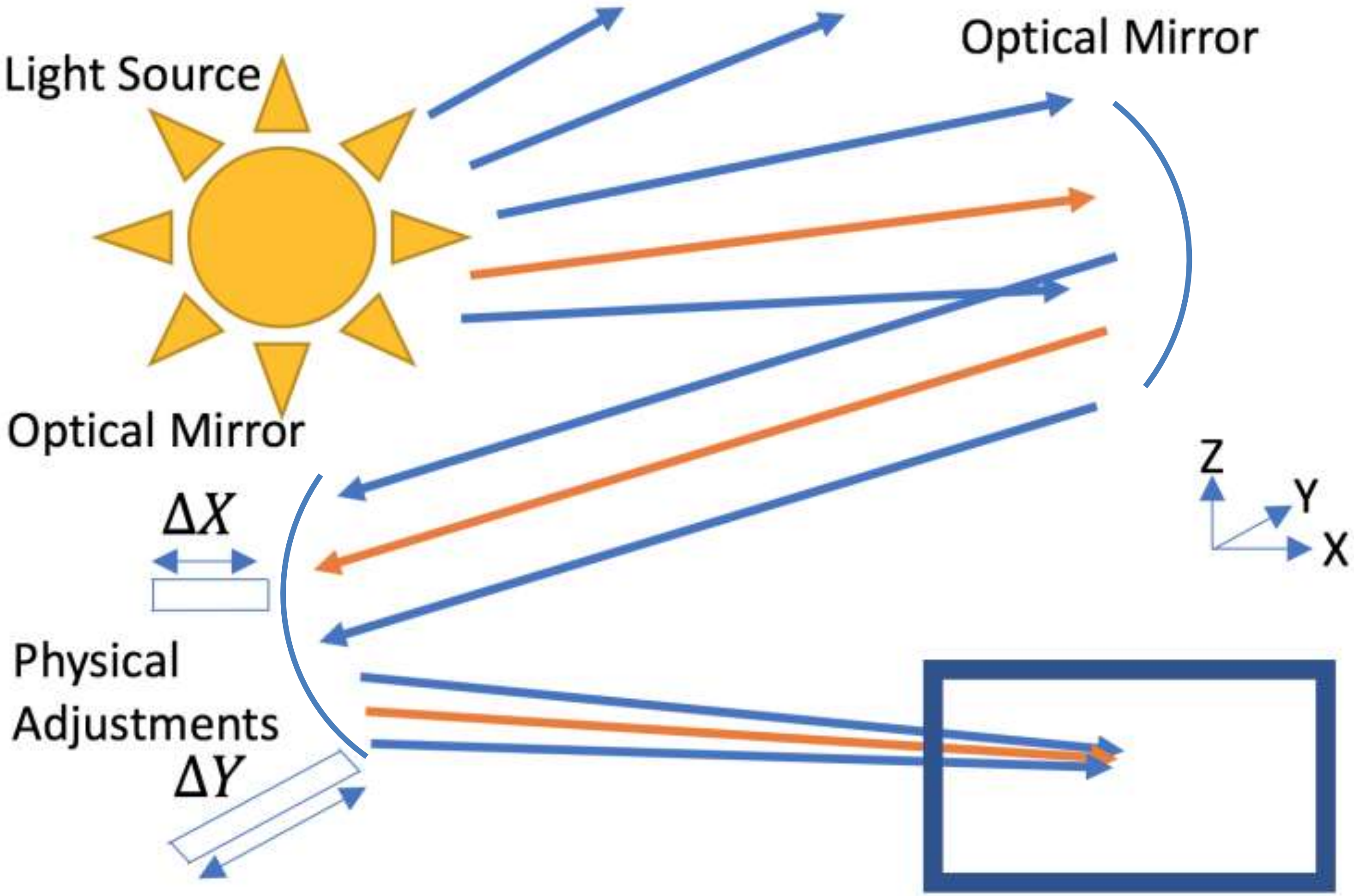
$$d\Delta X_i = \frac{dS}{W \cdot P}$$

1.3 - CONOPS

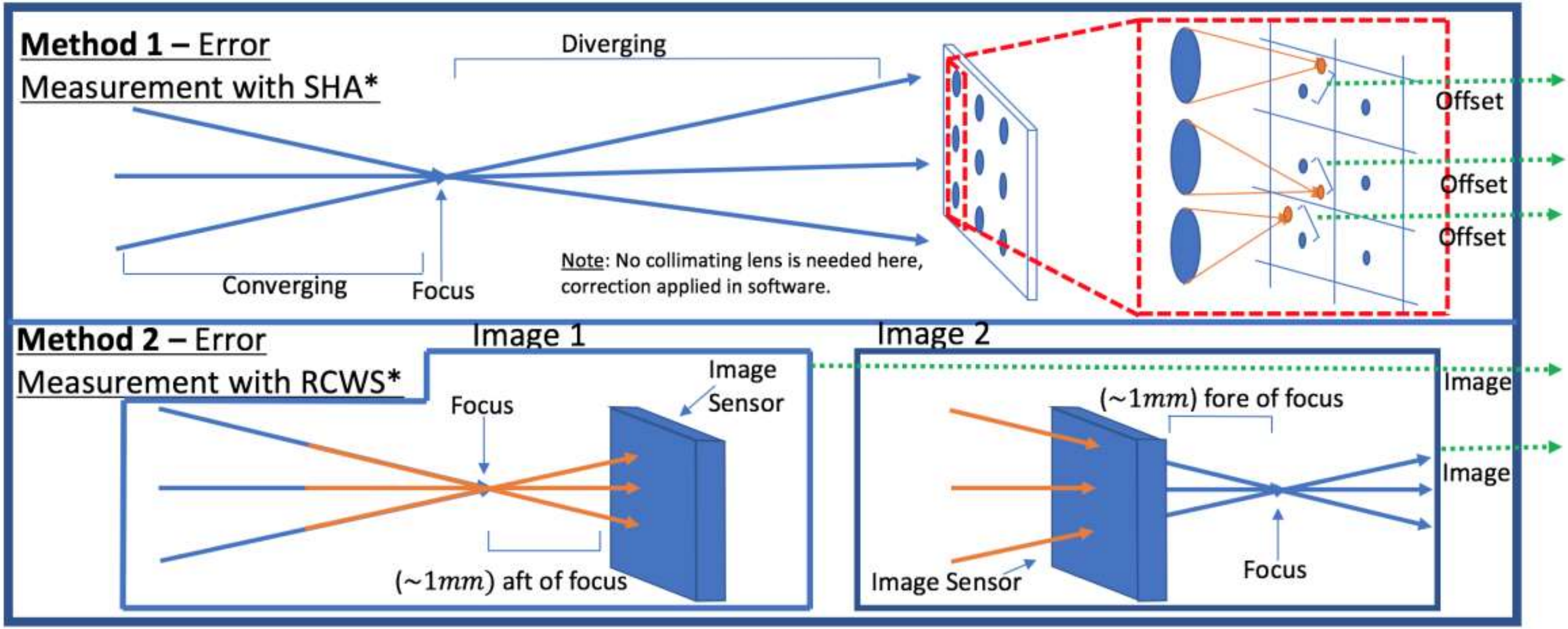


*See Nomenclature

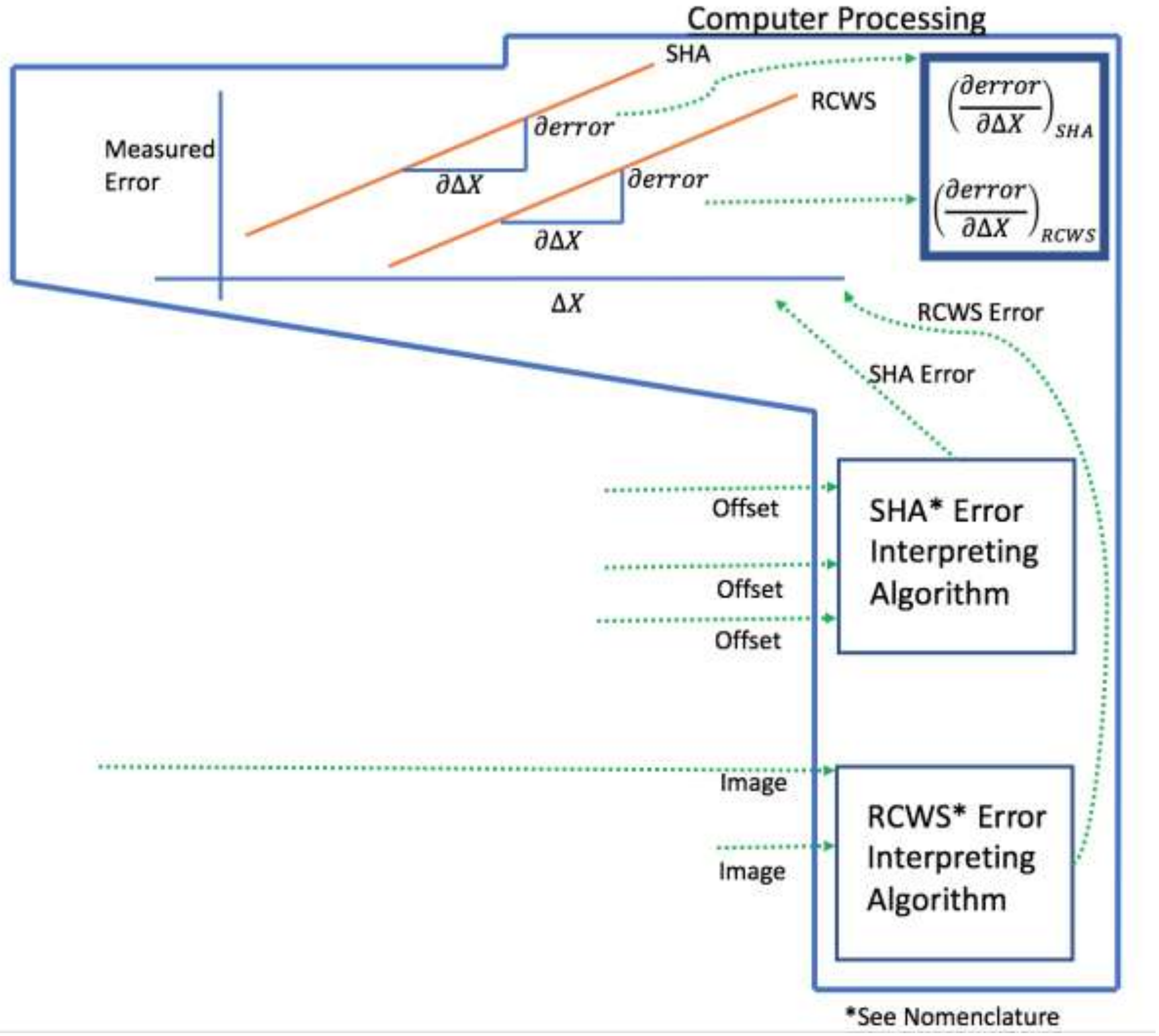
1.3 - CONOPS Part 1



1.3 - CONOPS Part 2



1.3 - CONOPS Part 3



*See Nomenclature

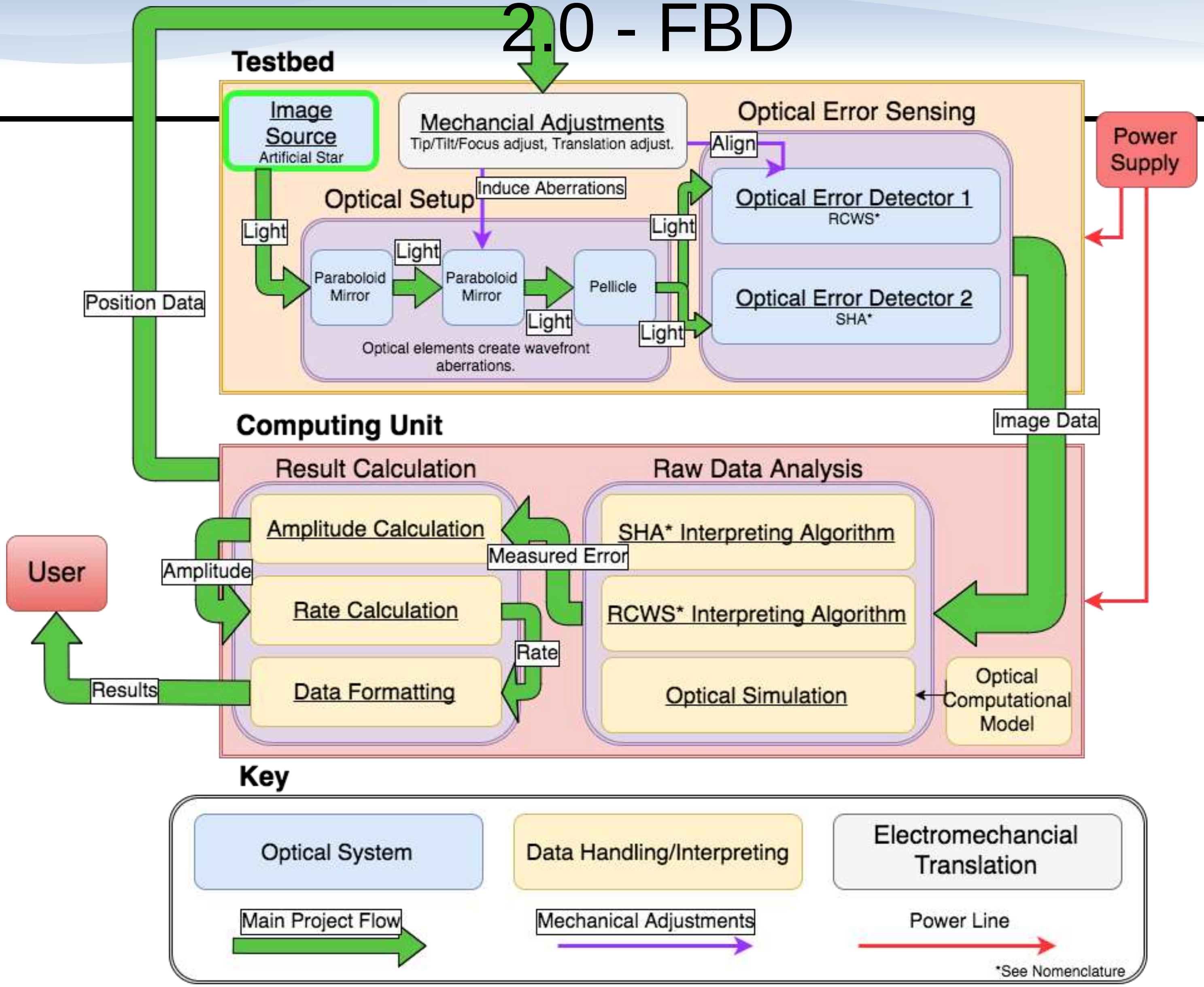
2.0 DESIGN SOLUTION

2.0 - Design Solutions

- The following section presents at a high level the design solution chosen to proceed

Element	Purpose
Image Source	Provide known conditioned state at the input to the system
Optical System	Introduce wavefront error and focus image to sensors
Shack-Hartmann Array	Test Article #1
Roddier Curvature Wavefront Sensor	Test Article #2
Testbed	Align, isolate, and protect optical components
Environmental Sensor System	Track environmental changes
RCWS Algorithm	Compute RCWS Zernike amplitudes from RCWS data
Test Control Software	Automate test procedure and perform data handling

2.0 - FBD



Testbed

Image Source
Artificial Star

Mechancial Adjustments
Tip/Tilt/Focus adjust, Translation adjust.

Optical Error Sensing

Align

Optical Setup

Induce Aberrations

Light

Paraboloid Mirror

Light

Paraboloid Mirror

Light

Pellicle

Light

Light

Optical Error Detector 1
RCWS*

Optical Error Detector 2
SHA*

Optical elements create wavefront aberrations.

Power Supply

Position Data

Image Data

Computing Unit

Result Calculation

Raw Data Analysis

Amplitude Calculation

Measured Error

SHA* Interpreting Algorithm

Amplitude

Rate Calculation

RCWS* Interpreting Algorithm

Rate

Data Formatting

Optical Simulation

Optical Computational Model

User

Results

Key

Optical System

Data Handling/Interpreting

Electromechancial Translation

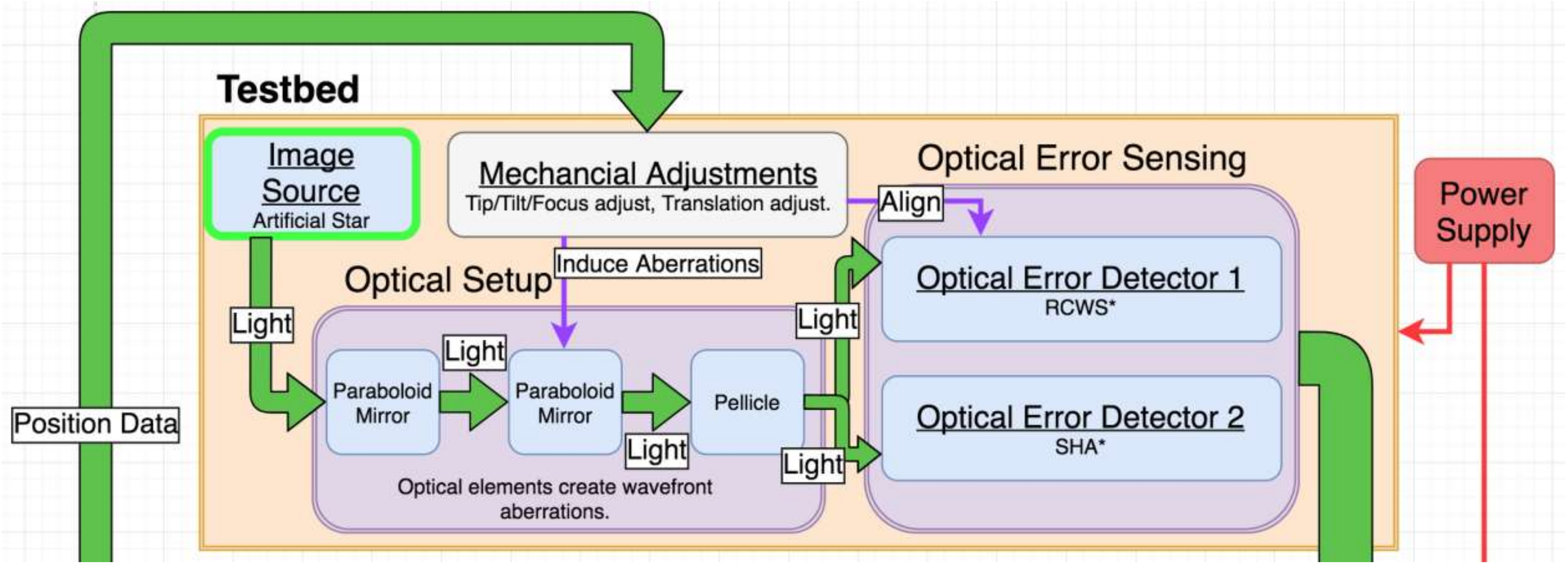
Main Project Flow

Mechanical Adjustments

Power Line

*See Nomenclature

2.0 - FBD Part 1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RCWS*
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Pellicle
Light
Light
Optical Error Detector 2
SHA*
Optical elements create wavefront aberrations.

2.0 - FBD Part 2

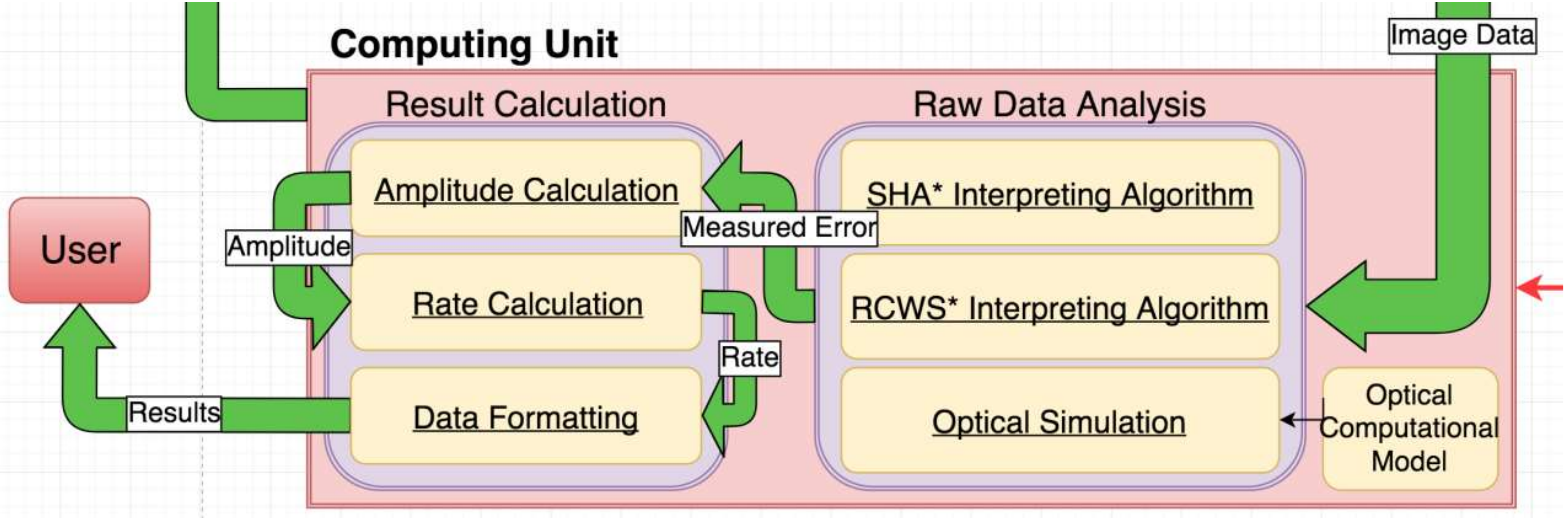
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Image Data
Result Calculation
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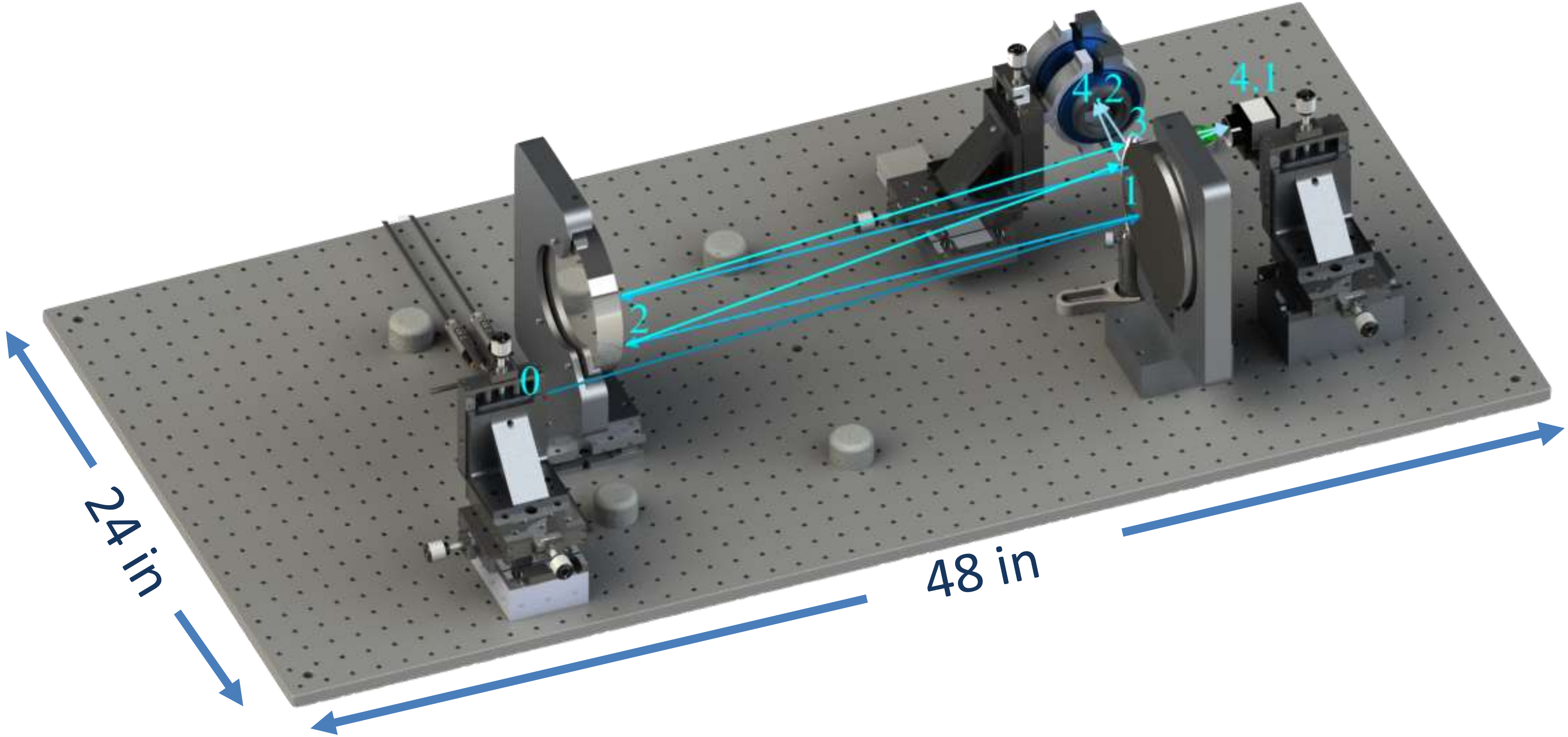
Amplitude Calculation
Rate Calculation
Data Formatting
SHA* Interpreting Algorithm
RCWS* Interpreting Algorithm
Optical Simulation
Optical Computational Model
Measured Error
Amplitude
Rate
Results
User

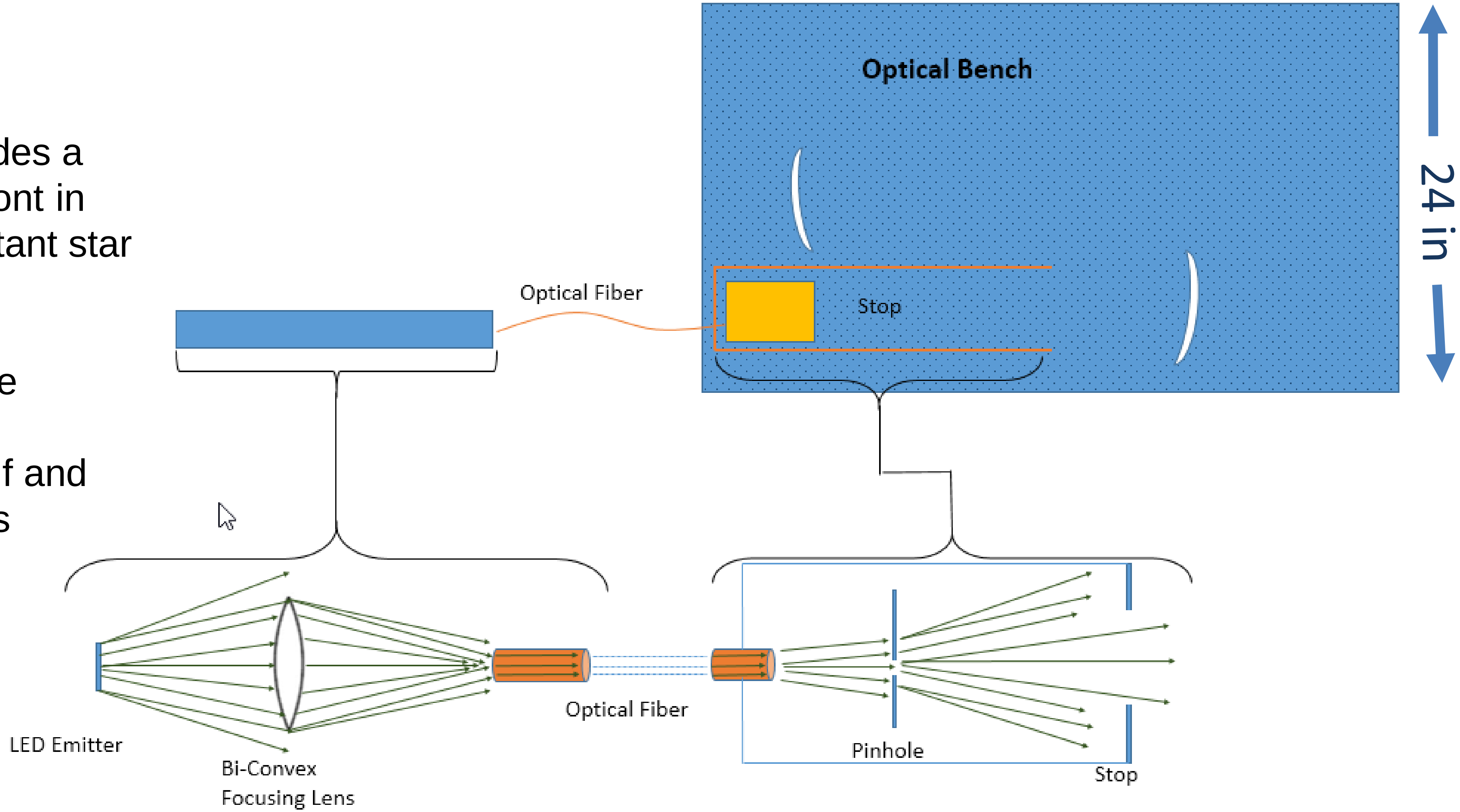
2.0 - System Overview



2.1 - Image Source

Purpose:

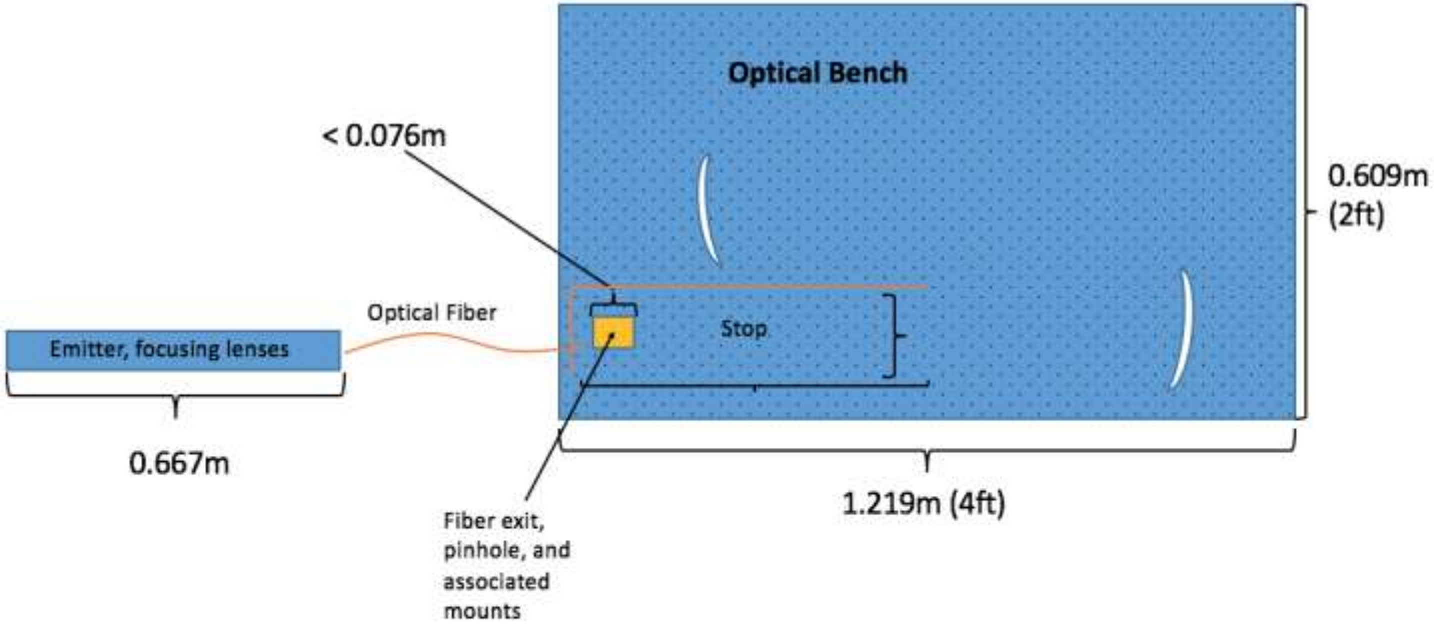
- The image source provides a spherical source wavefront in order to appear as a distant star to the image detectors.
- The source also tests the sensors over a range of intensities to determine if and when their performances diverge.



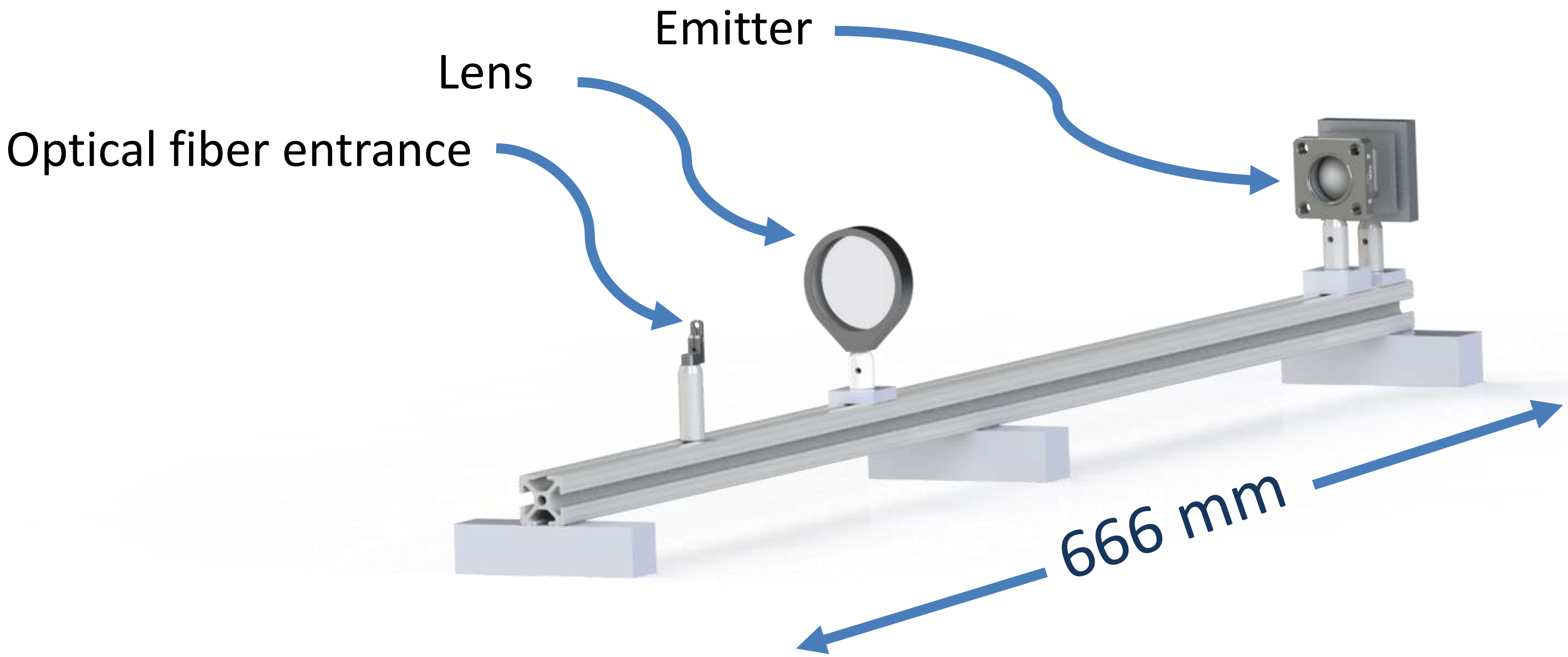
2.1 - Image Source

Requirements:

- The emitted wavefront must be spherical
- The source must emit a uniform intensity distribution
- The intensity of the source must be variable to 1/128 of the maximum intensity



2.1 - Image Source



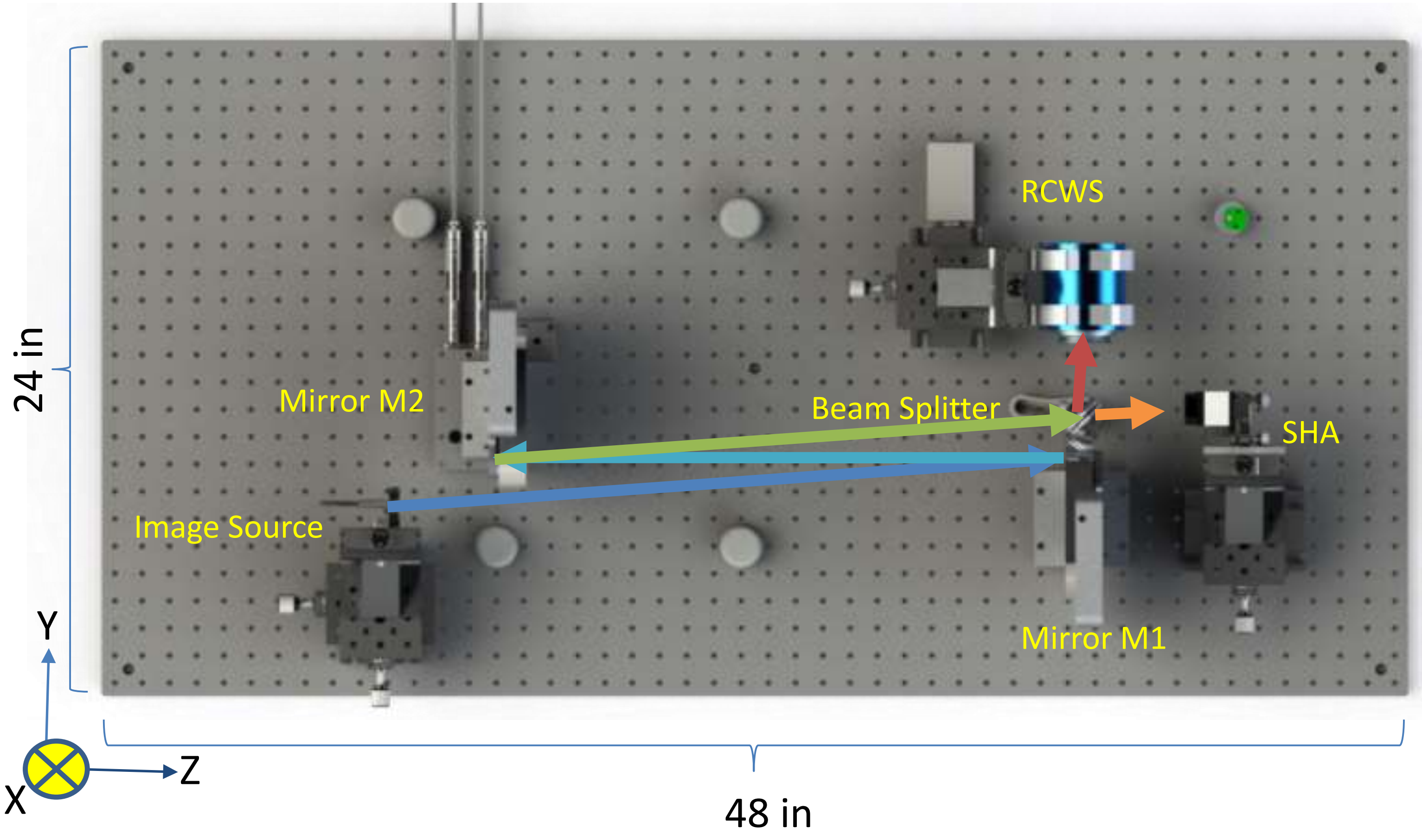
2.2 - Optical System

Purpose:

- Forms an image of the apparent distant image source
- Introduces known wavefront error by rotation of mirror M2

Requirements:

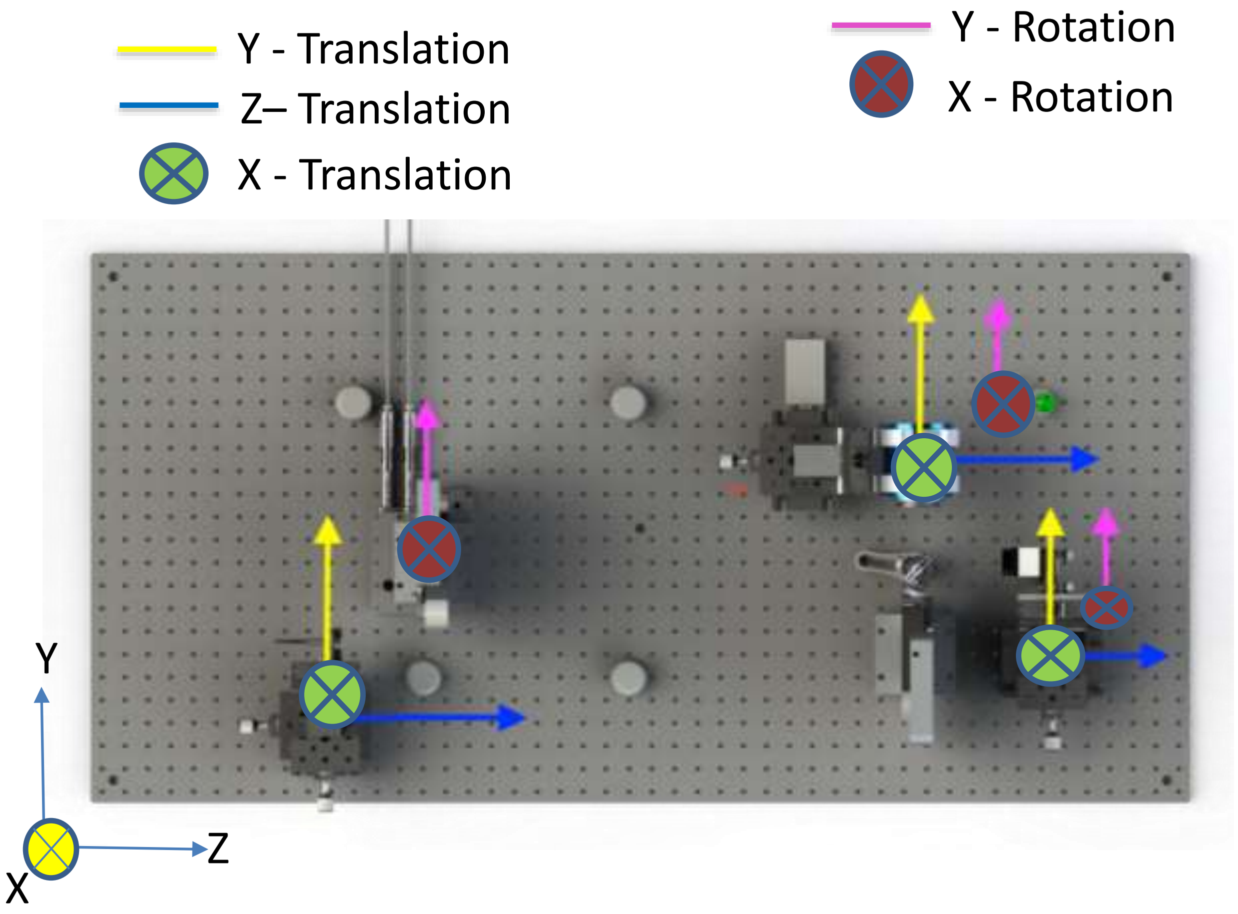
- Must introduce wavefront error in increments smaller than the desired detection resolution
- Introduce useful combinations of Zernike polynomial coefficients to fully test the RCWS algorithm



2.2 - Optical System

Alignment Degrees of Freedom

- Minimizing the number of degrees of freedom to fully align the system reduces resources spent on costly precision stages.
- Mirror 1 is fixed to the testbed, mirror 2 uses two rotational movements to align.
- The pellicle is large enough to remain fixed.
- The wavefront sensors must traverse to the focal point of mirror 2 and tilt in two directions to remove initial errors
- The image source must translate to the focal point of mirror 1.



2.3 - Wavefront Sensors

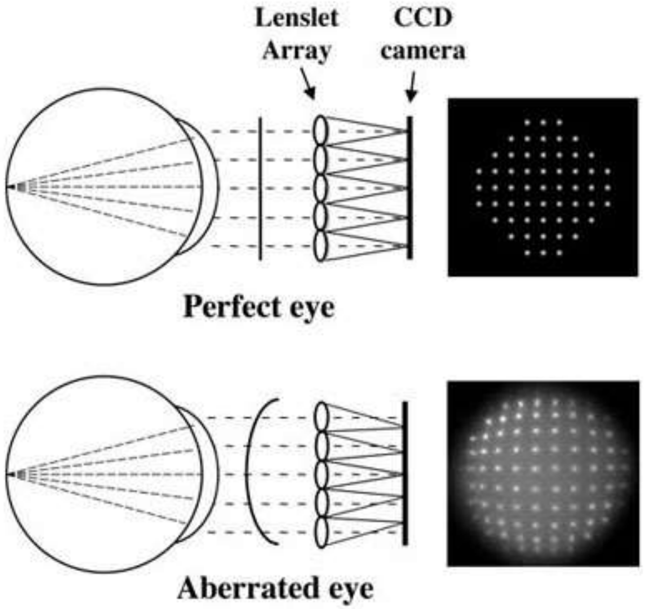
Purpose:

- The wavefront sensors are the test articles for the experiment.

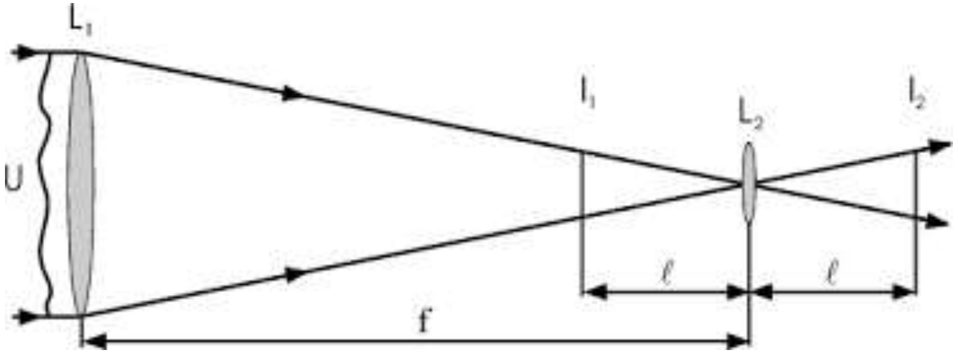
Requirements:

- A Shack-Hartmann Array sensor from Thorlabs will be provided
- A Roddier Curvature Wavefront Sensor must be developed using COTS components

Shack-Hartmann Array:



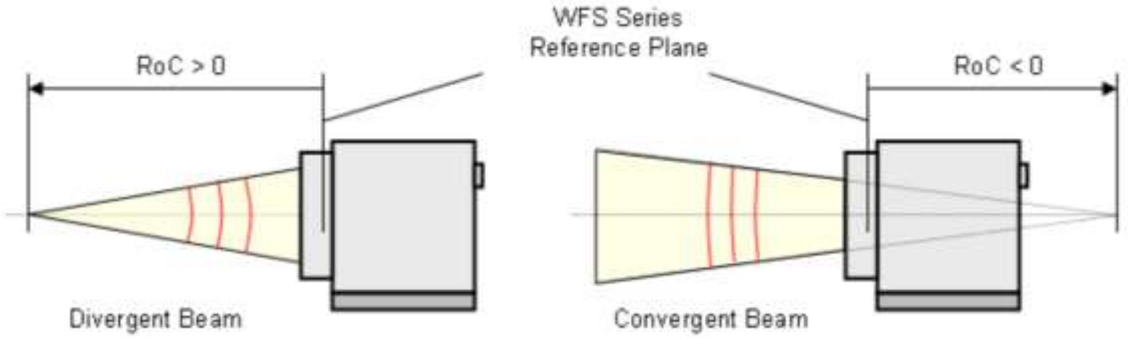
Roddier Method:



2.3 - Wavefront Sensors

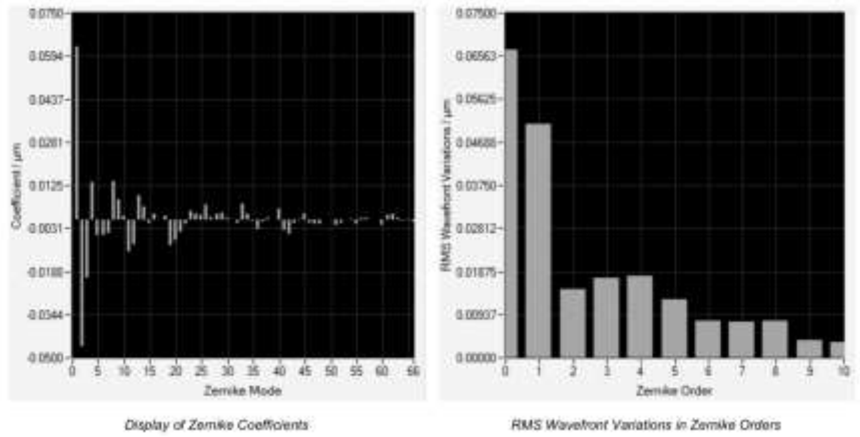
Shack-Hartmann Array

- Provided by the customer
- Interfaces to a PC over USB
- Supplied with software to determine standard Zernike coefficients
- May be operated without a collimating lens in a divergent or convergent beam



Operation of WFS150-7AR in a divergent/convergent beam

Thorlabs WFS150-7AR [7]



Zernike coefficient output from Thorlabs provided software

2.3 - Wavefront Sensors

Roddier Curvature Wavefront Sensor

- Developed from COTS parts because no commercial RCWS exist
- Comprised of CMOS camera and precise linear traverse for defocus
- CMOS and travers interface to PC via USB
- Two CMOS detectors provided by the customer
    - ASI120MM
    - QHY174M

5.86µm pixels:
Low shot noise:

3.75µm pixels:
Small detector:

QHY174M CMOS Detector [3]

ASI120MM CMOS Detector [2]

Thorlabs PT1-Z8 traverse [4], 50 nm step size, 1 inch travel

2.4 - Environmental Sensors

Purpose:

- Record thermal and vibrational data during test sequence to verify that error sources are below threshold.

Requirements:

- Accelerometers must be able to correctly capture frequencies up to 300 Hz, and sample at 1kHz (Requirements: 6.1, 6.3)
- Temperature sensors must be able to measure at a minimum resolution of 0.15 K, a minimum accuracy of 0.5 K, and sample at a rate of 1Hz (Requirement: 6.2)
- Sensor data shall be communicated to the testbed control computer for the duration of the test sequence (Requirement: 6.4)

Overview

- 12 total sensors – 6 temperature and 6 accelerometers – will be placed throughout the testbed and the optical components to collect local environmental data.
- The sensors will be interfaced with a microcontroller to relay data to a computer

2.4 - Environmental Sensors

- **Component Choices:**
  - Microcontroller: Teensy 3.6
  - PC Interface : Serial USB connection
  - Accelerometer: ADXL 344
  - Temperature Sensor: ADT7320
  - Overall Schematic

ADXL344 Requirements and Performance

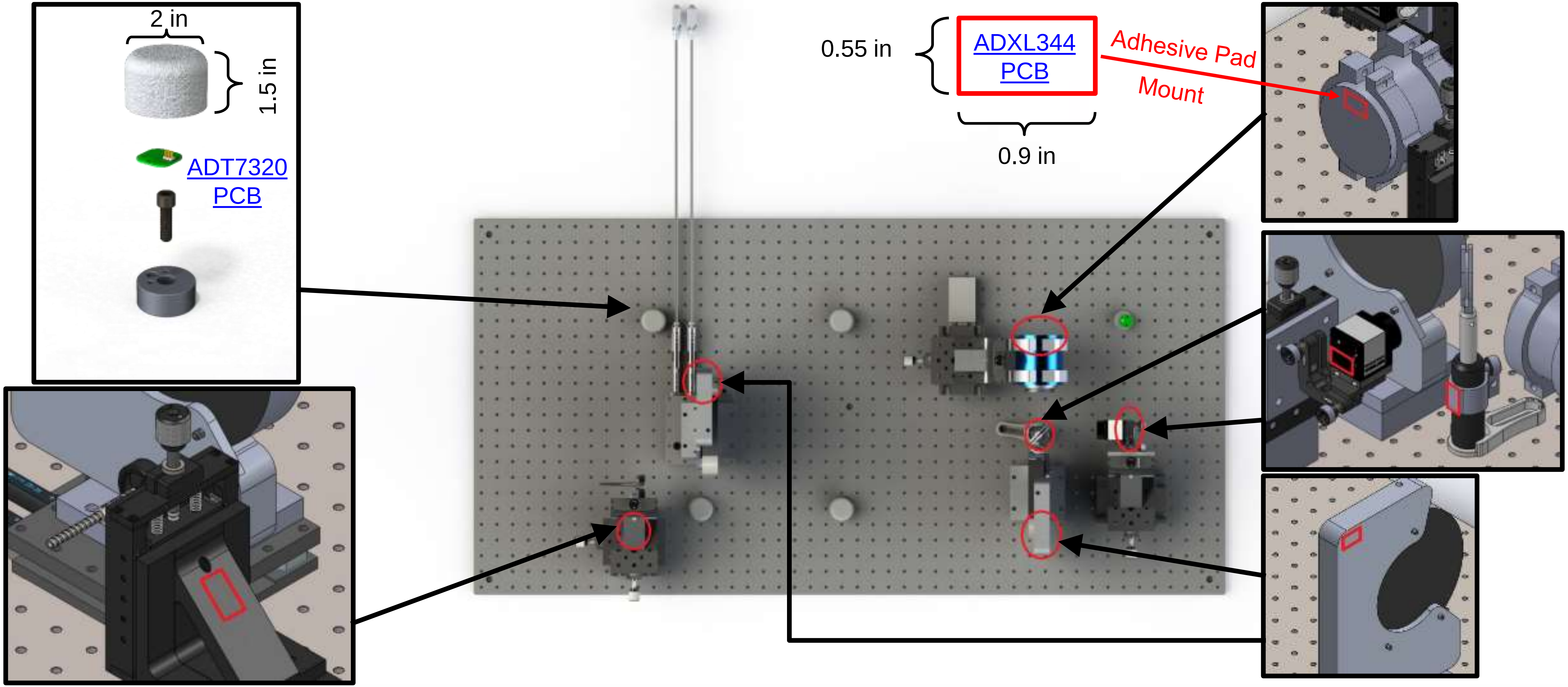
	Sampling Rate	SPI Data Rate	Resolution	Filtering?
Requirement:	1 kHz	0.55 MHz	NA	Yes
ADXL-344 Performance	3.2 kHz (Maximum)	5 MHz ($\approx 5\ Mbps$)	$\pm 3.9mg$	Yes

ADT7320 Requirements and Performance

	Sampling Rate	SPI Data Rate	Resolution 16 bit (13 bit) [°C]	Accuracy [°C]	Filtering?
Requirement:	1 Hz	0.55 MHz	± 0.15	± 0.5	No
ADT7320	4 Hz (Maximum)	5MHz ($\approx 5Mbps$)	± 0.0078 (± 0.0625)	± 0.31	No

2.4 - Environmental Sensors

Sensor Locations



2.5 - Testbed

Purpose

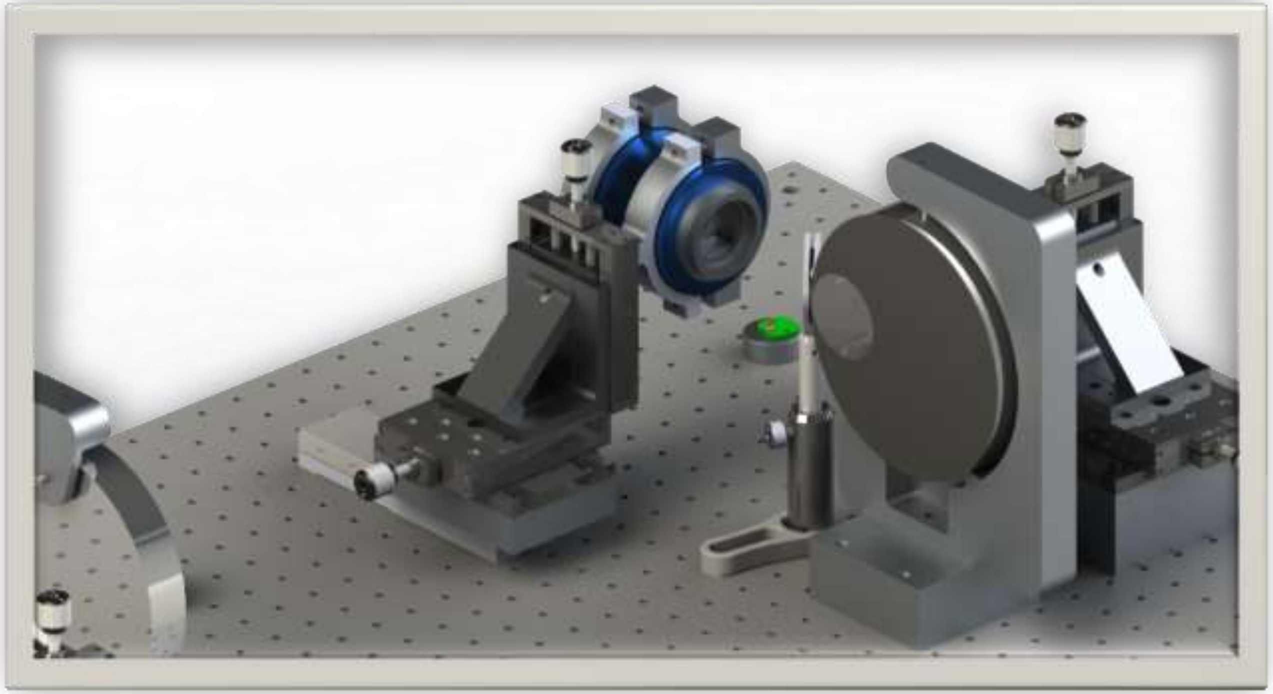
- The testbed allows for alignment and structural support of the optical elements.
- The testbed also provides thermal and vibrational effect damping.
- The testbed reduces external light contamination.

Requirements

- The testbed must allow for alignment of individual elements to within 1% change in Strehl ratio.
- The test area must be contained within a 2' x 4' section

Overview

- Degrees of freedom for alignment other than the RCWS traverse and M2 tip/tilt platform will be set using manual PT1B traverses and KM100WFS tip/tilt stages from Thorlabs.



2.5 - Testbed

Test Location:

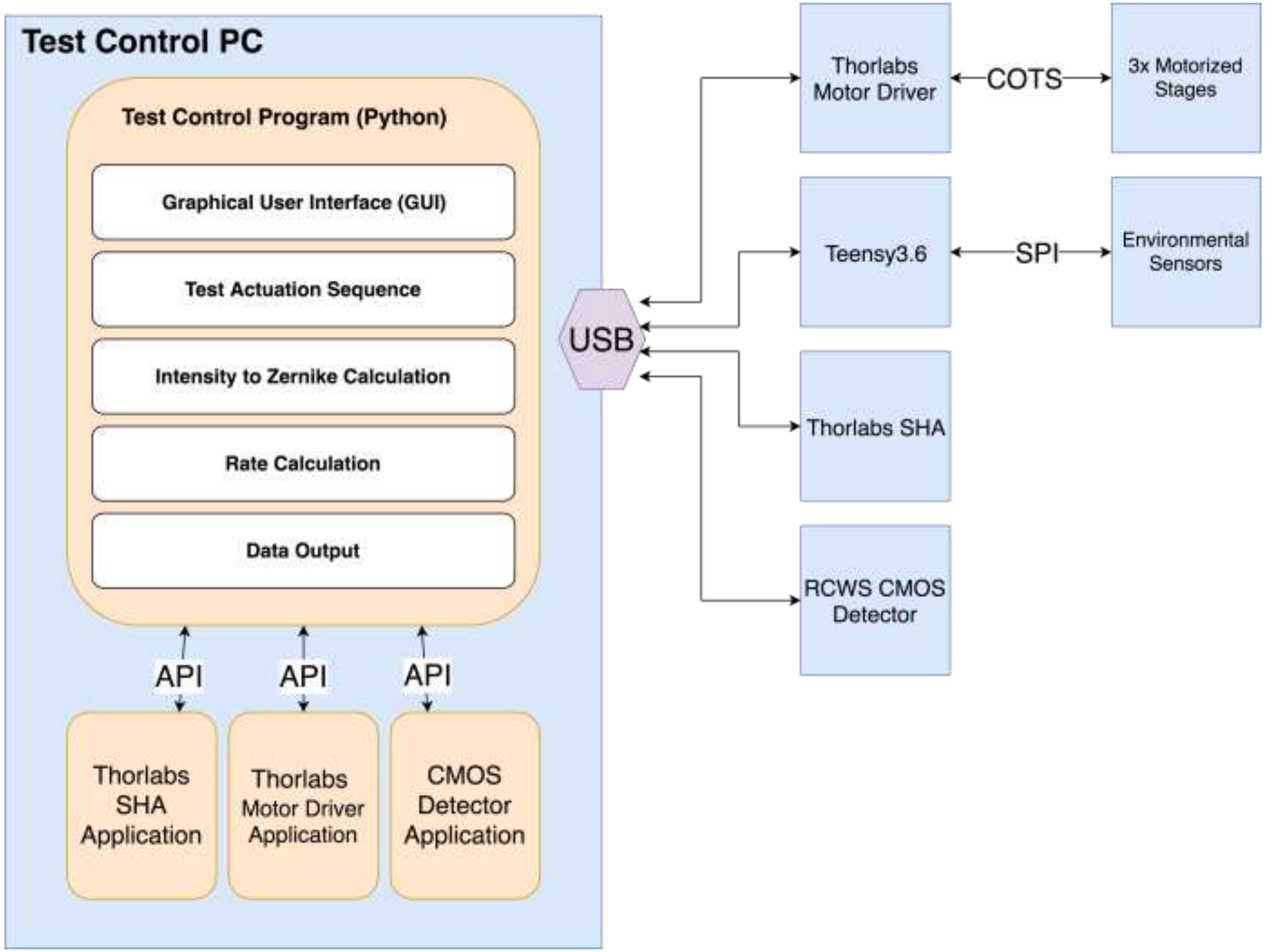
- SwRI: 1050 Walnut St. Boulder CO.
  - 1.5 miles from CU engineering center with public transit available
  - Sharing optical table space (allotted 2'x4' section)
  - Allotted 6 week minimum residence

Optical Table:

- Newport RS2000
- 10' x 5' x 2'
- 1 inch spaced ¼-20 tapped holes
- Tuned damping and CTE
- Vibration isolating legs

Optics table from Newport [1]

2.6 - Test Software



Purpose:

- Automate test execution.
- Enable larger data sets to be collected.
- Reduce human error.
- Improve ease of recording and transporting data.

Requirements:

- Interface with motorized stages
- Interface with wavefront sensors
- Interface with environmental sensor system
- Execute a specified test plan given mirror tilts, RCWS defocus distances, and receive intensities
- Compute Zernike amplitudes given RCWS intensity and defocus data
- Compare response on RCWS to SHA

3.0 CRITICAL PROJECT ELEMENTS/ 4.0 DESIGN REQUIREMENTS AND THEIR SATISFACTION

3/4 - Critical Project Elements and Design Requirements and Satisfaction

Test Platform Considerations:

- Obtaining quality scientific data about the performance of the two sensors is key.
- Most critical elements are concerned with reducing or reporting error in the test.
- Other key CPE's stem from customer-specified requirements.

In consideration the following section will present key CPE's alongside the models that validate the design choices made in the platform

Design Element	Key Critical Project Elements
Image Source	Image Size, image Intensity, image variation, image stability
Optical System	Introduction of Zernikes, resolution of introduced error
Roddier Curvature Wavefront Sensor	Defocus plan, image spill
RCWS Algorithm	Bi-directional operation, RCWS reading interpretation
Environmental Sensor System	Thermal sensitivity, vibrational sensitivity, sensor placement, and data rate

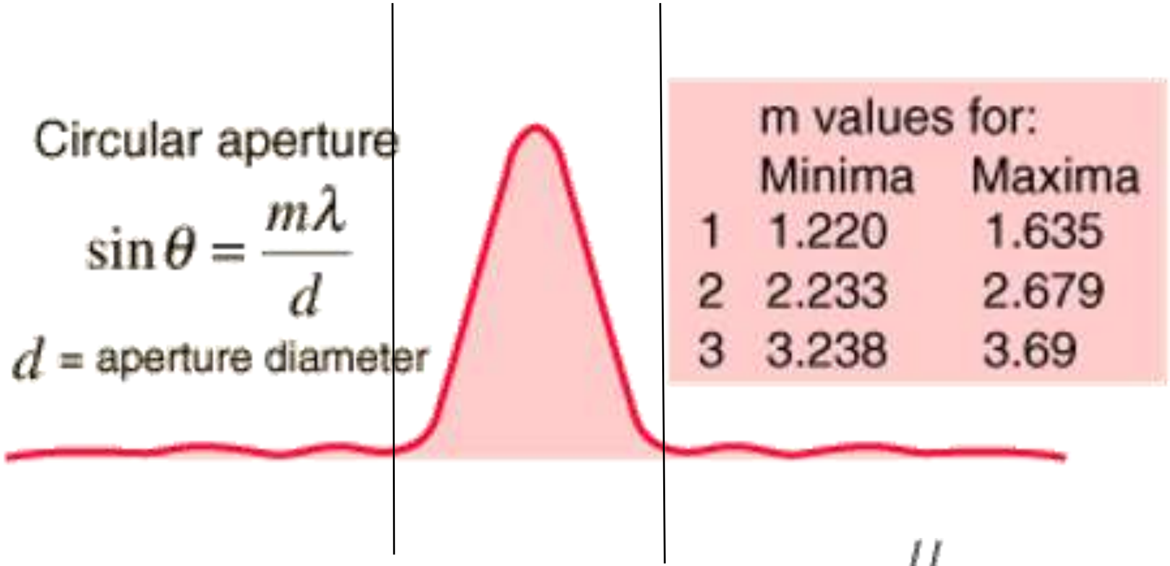
3.1/4.1 - Image Size

Critical Factor:

- The source must emit a spherical wavefront, otherwise the optimal alignment will exhibit wavefront error that may wash out intentional aberrations

Model:

- The pinhole stops acting as a point source when the diameter exceeds the size out to the first minimum of the diffraction pattern.
- Pinhole diameter at 550nm center wavelength can be at most about 16 µm
  - Worst case value using blue light (smallest wavelength) yields 13 µm
  - Standard 10 µm pinhole suits needs, and is readily available



$$\sin\theta = \frac{m\lambda}{d}$$

m values for:

	Minima	Maxima
1	1.220	1.635
2	2.233	2.679
3	3.238	3.69

$$D_{max} = 2.44\lambda f^{\#}$$

$$f^{\#} = \frac{f}{d_{aperture}} = 12 \quad \lambda_{center} = 550nm$$

$$D_{max} = 16.1\mu m$$

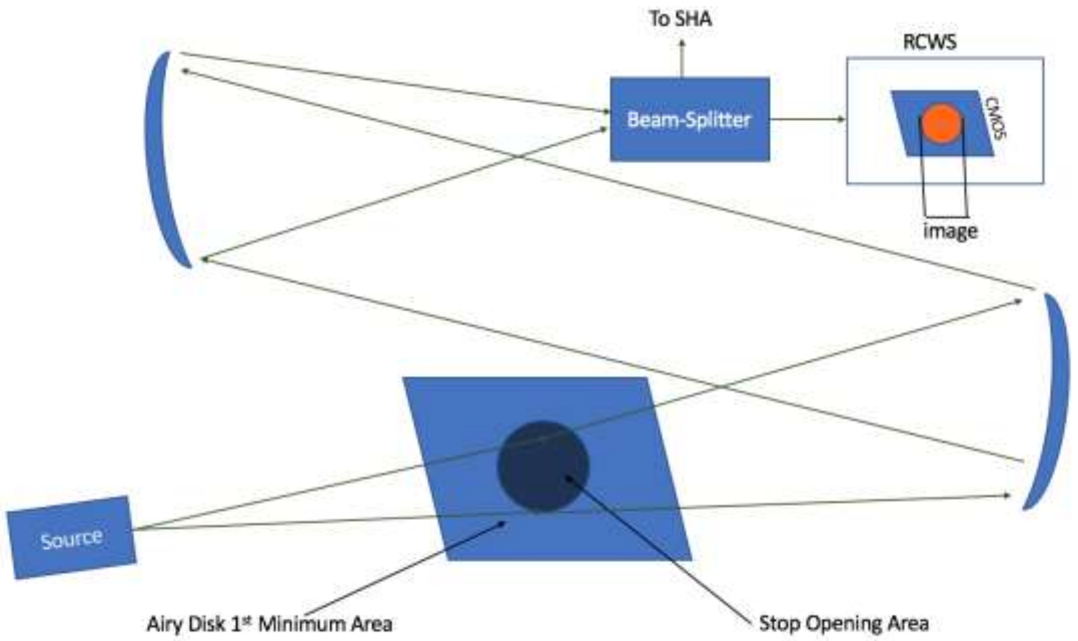
3.2/4.2 - Image Source Maximum Power Output Required

Critical Factor:

- The image source must produce enough intensity to meet 10,000 photons per exposed pixel on average in order to obtain maximum SNR of 100

Model:

- Developed MATLAB model to determine if source design can meet minimum light requirement
- Major assumptions:
  - No Light scattering
  - All light reflected off M1 hits M2
  - Only interested in first airy minimum, which typically contains 83% of intensity
- Results:
  - 6.140663e-09 watts of light required out of pinhole



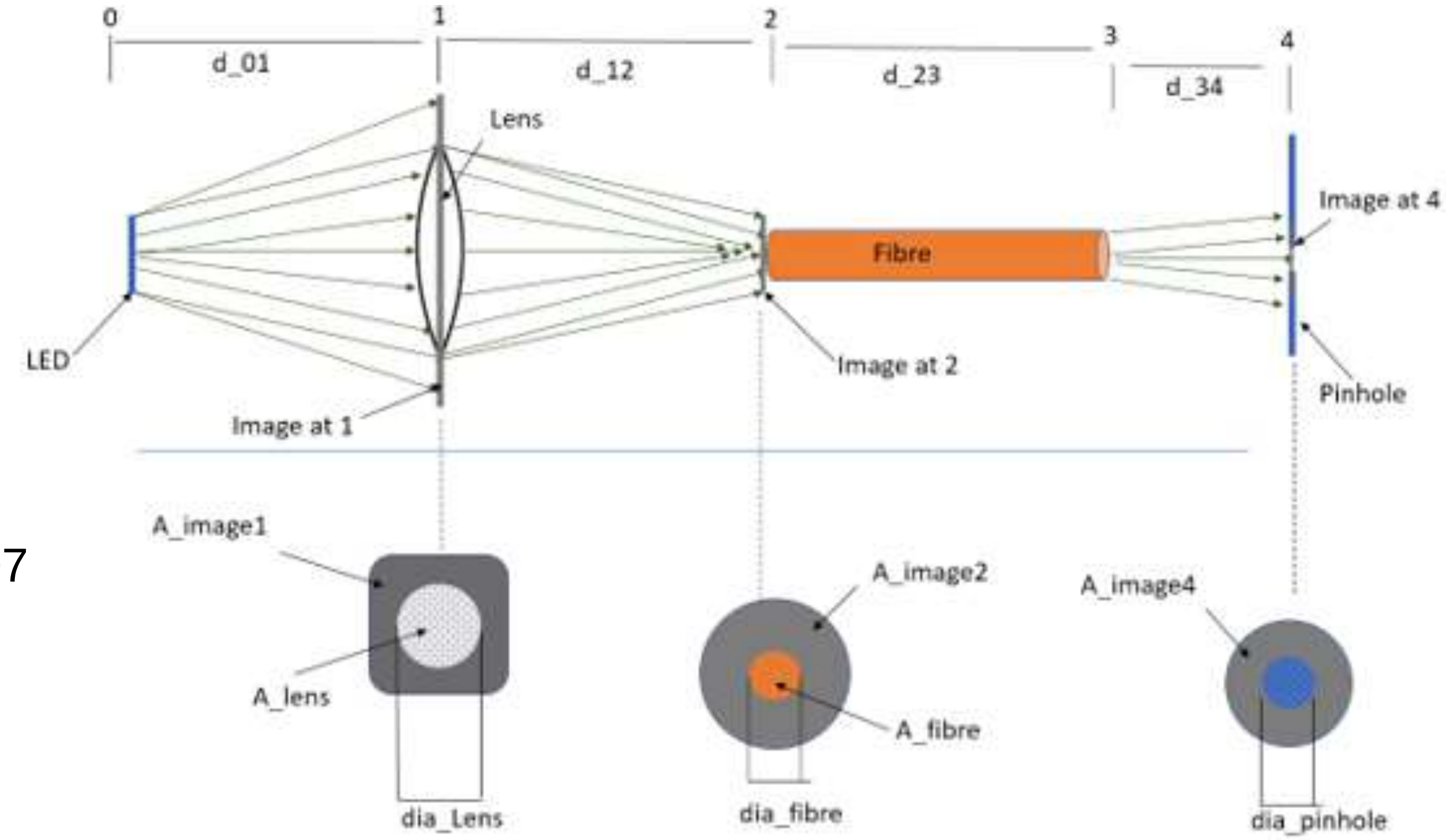
3.3/4.3 - Maximum Power Output Produced

- Major assumptions:
  - LED emits isotropically
  - Thin lens assumption
- Major equations:
  - Thin lens equation:

Thin Lens Equation

$$\frac{1}{d_0} + \frac{1}{d_i} = \frac{1}{f}$$

  - Trigonometry
- Results:
  - This configuration can output 1.9496e-07 watts
- This is more than enough to satisfy the requirement previously stated



3.4/4.4 - Image Intensity Variation

Critical Factor:

- The received intensity must vary across a range to determine at what conditions the performance of the two wavefront sensors diverge.

Model:

- Changing image intensity is most easily achieved by varying exposure time of the detector
- Simple relationships where number of photons onto detector is directly related to exposure time
- Results:
  - Exposure 16.67ms (1/60 seconds) to 130.2µs (1/7680 seconds)
  - Both RCWS and SH array can accommodate this range
    - RCWS Range: 50µs to 1800s
    - SHA Range: 79µs to 65ms
- Full range of 1 to 1/128 of full intensity is achievable using shutter speed adjustment in software

$$E_{total} = P_{emitter} * t_{exp}$$

$$\frac{\#_{photons}}{\#_{pixels}} = \frac{E_{total}/E_{\gamma}}{\#_{pixels}}$$

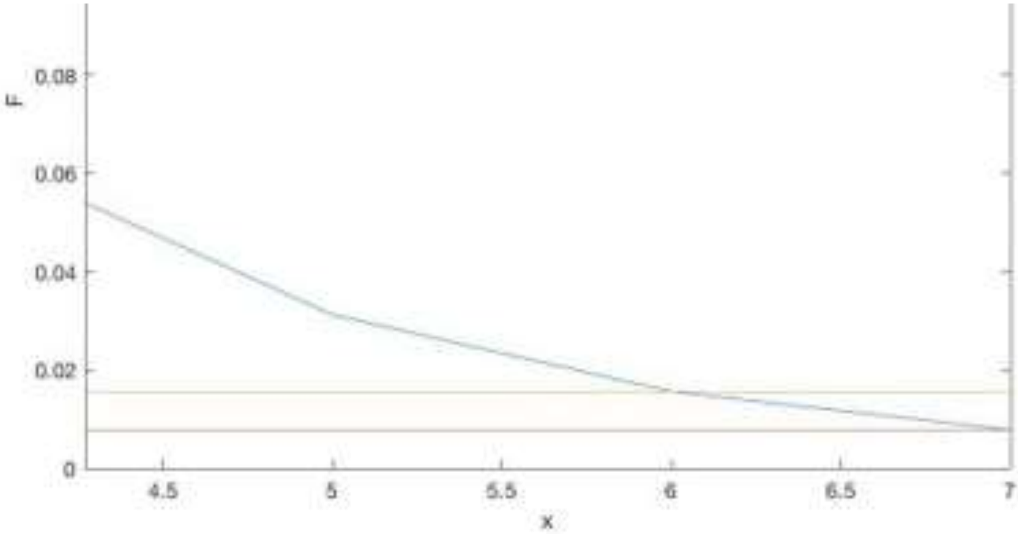
3.5/4.5 - Image Source Stability

Critical Factor:

- Operation of the RCWS is based on the gradient of intensity over the defocus range. In the time spent translating by the RCWS detector intensity fluctuations from the image source may impart unacceptable error in measured Zernike amplitudes.

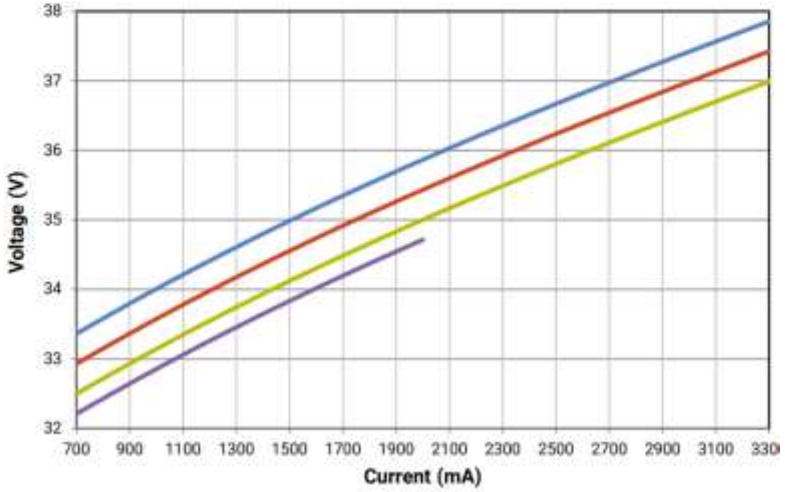
$$P_{LED}(x) = P_{LED_0} * F(x)$$

$$F = 2^{-x}$$



Model:

- Stability analysis was done to determine maximum allowable current ripple of LED power supply
- LED Intensity needs to go from full power to 1/128 in scales of ½
- Which gives smallest change in LED output power and then smallest change in input current
- Results: 15.5566 mA is the largest allowable current ripple
- Chosen Meanwell HLG-60H-36A power supply has ripple of approximately 7mA



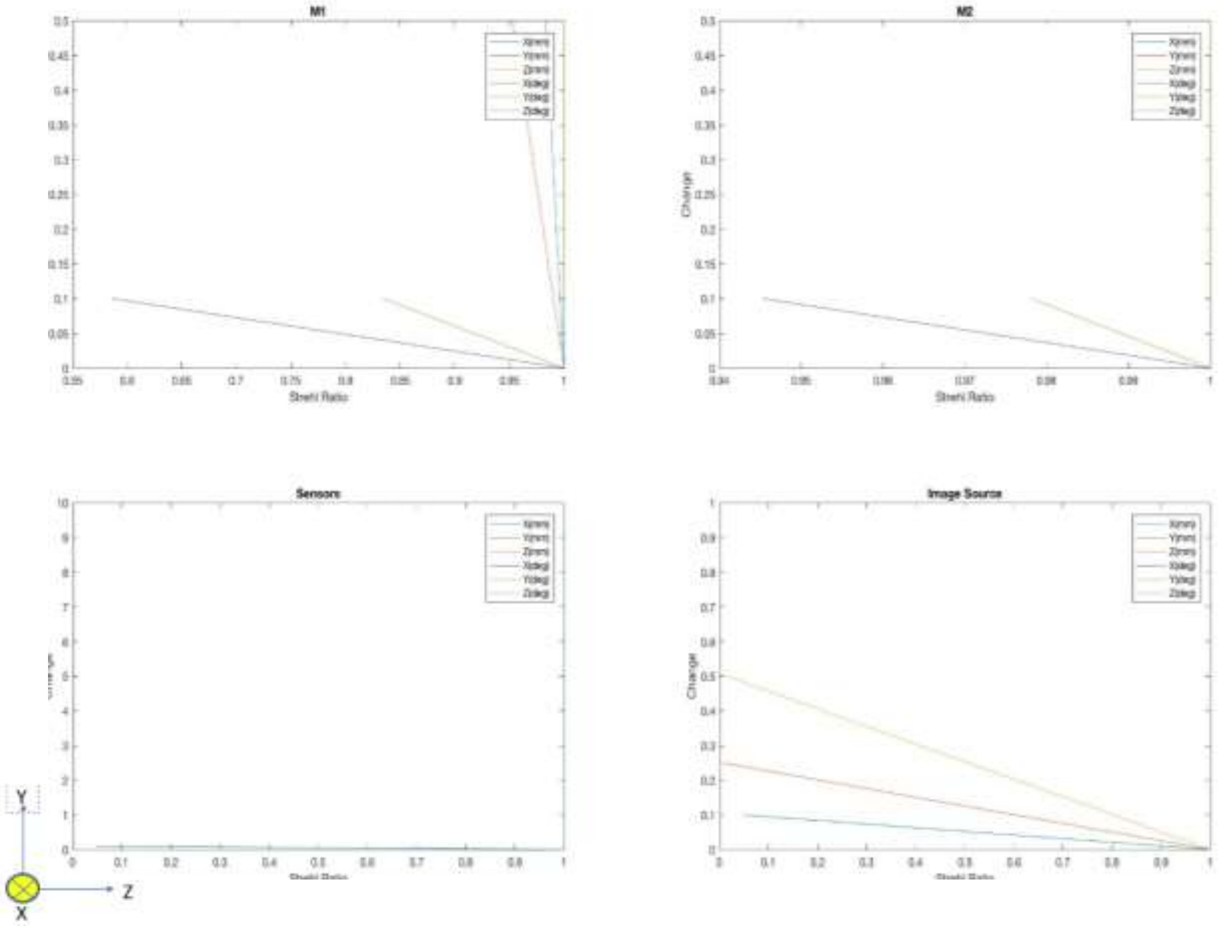
3.6/4.6 - Optical System Error Introduction

Critical Factor:

- The customer has specified that the resolution of wavefront error at which the sensors shall be compared is a 1/50 change in Strehl ratio. In order to make this comparison the optical system must introduce error at least at this resolution.

Model:

- Zemax used to obtain linearized Strehl and Zernike sensitivities about a perfectly aligned system.
- Small angle approximation used to determine tip and tilt that produce 1/100 change in Strehl ratio.
- Results
  - Tip/tilt resolution minimum is 216 arc seconds
- Tip/tilt platform step size is 15 arc seconds



3.7/4.7 - Tip/tilt to Zernike Transfer Function

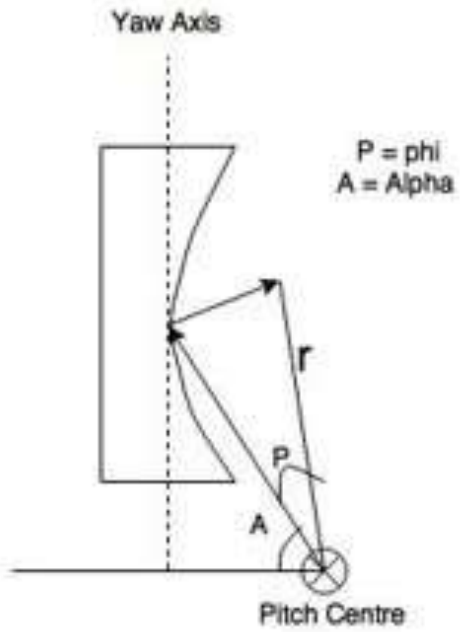
Critical Factor:

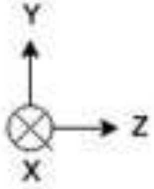
- Need to feed Zemax model actual mirror aberration in 6 DOF for result verification.
- Unique Zernike modes need to be introduced to sufficiently test the RCWS algorithm.

Model:

- Mechanical movement modeled geometrically.
- Introduced Zernike modes linearized about S=1 system using Zemax.
- Vector r gives both translational and rotational offsets of the mirror.
- Vector z gives first 12 Zernike mode coefficients.
- Sensitivities of Zernike modes to 6 DOF of mirror are given in matrix M.

$$\hat{r} = \begin{bmatrix} x_t \\ y_t \\ z_t \\ x_r \\ y_r \\ z_r \end{bmatrix}$$



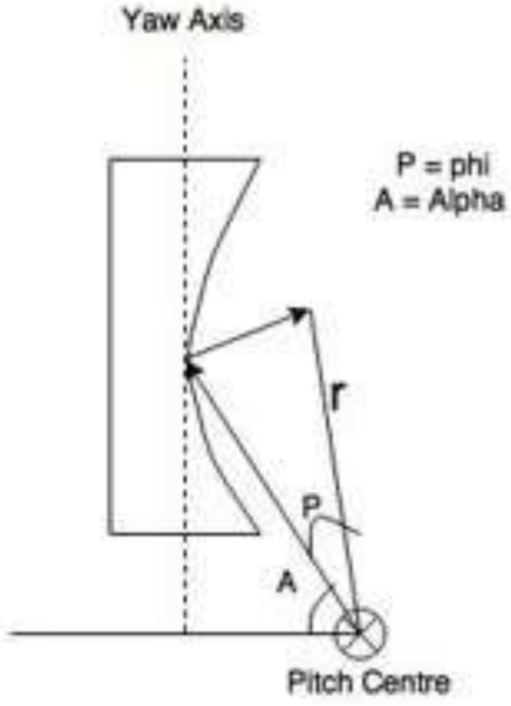


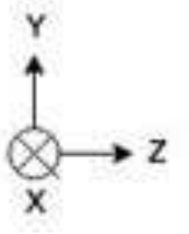
$$\hat{z} = \begin{bmatrix} z_1 \\ . \\ . \\ . \\ z_{12} \end{bmatrix}$$

3.7/4.7 - Tip/tilt to Zernike Transfer Function

$$\hat{r} = T \begin{bmatrix} \theta \\ \phi \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \phi r \cos\alpha \\ 0 & \phi r \sin\alpha \\ 0 & 1 \\ 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \phi \end{bmatrix} \qquad \hat{z} = MT \begin{bmatrix} \theta \\ \phi \end{bmatrix}$$

$$M = \begin{bmatrix} 0 & 0 & -0.6148 & -0.5449 & 0.0494 & 0 \\ 0 & 0 & 0 & 0 & -0.0842 & 0 \\ 0 & 0 & -0.0013 & 0.0844 & 0.00007 & 0 \\ 0 & 0 & -0.3548 & -0.3145 & 0.0285 & 0 \\ 0 & 0 & 0 & 0 & 0.2306 & 0 \\ 0 & 0 & 2 \cdot (10^{-6}) & 0.2282 & 0.01 & 0 \\ 0 & 0 & -4.746 \cdot (10^{-4}) & 0.0298 & 2.5 \cdot (10^{-5}) & 0 \\ 0 & 0 & 0 & 0 & -0.0298 & 0 \\ 0 & 0 & 0 & 4.8 \cdot (10^{-4}) & 1.625 \cdot (10^{-5}) & 0 \\ 0 & 0 & 0 & 0 & -4.825 \cdot (10^{-4}) & 0 \\ 0 & 0 & 1.063 \cdot (10^{-4}) & 1.2667 \cdot (10^{-4}) & -7.5 \cdot (10^{-6}) & 0 \\ 0 & 0 & 3.333 \cdot (10^{-7}) & -1.0067 \cdot (10^{-4}) & -1.667 \cdot (10^{-6}) & 0 \end{bmatrix}$$





Result:

- A well-defined relationship between the commanded pitch and yaw angles and the output Zernike amplitudes has been found.
- Can be applied to feed predictive models in the test phase
- Given enough mirror deflection it is possible to set any two Zernike amplitudes.
- However there are limiting factors such as beam spill and optical table real estate that will limit the reachable solutions.

3.8/4.8 - RCWS Defocus Plan

Critical Factor:

- Minimize error within the RCWS system with an optimal defocus distance.

Model:

Purpose:

- Experimentally determining the optimal defocus distance of the RCWS.
- This is difficult to determine analytically, so an experimental approach will be taken.

Limitations:

- Compares performance to the Shack Hartmann Array.
- Uses discrete 0.05 inch jumps in RCWS defocus distance.

Assumptions:

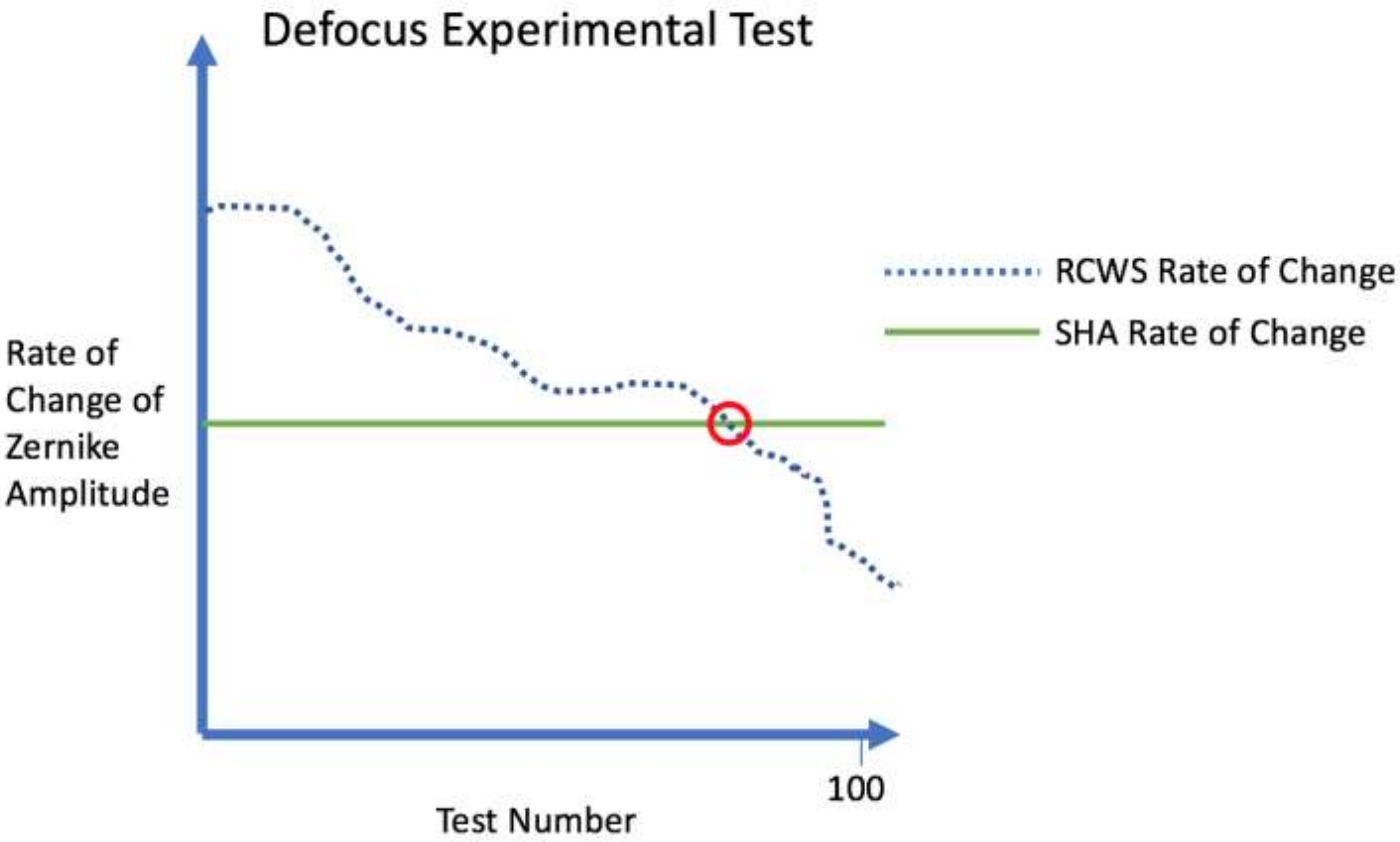
- The Shack Hartmann Array is correctly calibrated.
- Image intensity is constant over all tests.
- Image sensor exposure time is constant over all tests.
- Optimal translation distance for each intensity is constant over all tip/tilt angles.
- Rate of change over each set of tests is linear.

3.8/4.8 - RCWS Defocus Plan

- All 100 tests are conducted at the same intensity.
- These tests will then be repeated for each new intensity, as the optimal defocus could be different for each intensity level.
- Each set of five tests will be utilized to determine the rate of change of

Test #	RCWS Displacement (inches)	Tip/Tilt (degree)
1-5	0.05	0-0.135
6-10	0.10	0-0.135
11-15	0.15	0-0.135
16-20	0.2	0-0.135
21-25	0.25	0-0.135
26-30	0.3	0-0.135
31-35	0.35	0-0.135
36-40	0.4	0-0.135
41-45	0.45	0-0.135
46-50	0.5	0-0.135
51-55	0.55	0-0.135
56-60	0.60	0-0.135
61-65	0.65	0-0.135
66-70	0.70	0-0.135
71-75	0.75	0-0.135
76-80	0.80	0-0.135
81-85	0.85	0-0.135
86-90	0.90	0-0.135
91-95	0.95	0-0.135
96-100	1	0-0.135

3.8/4.8 - RCWS Defocus Plan



- The expected form of results from Defocus testing.

- The only variable is the RCWS defocus, which won't affect the performance of the SHA. As such, the SHA performance is constant.

3.9/4.9 - Detector Image Spill

Critical Factor:

- The image must stay on the RCWS image sensor during the course of a capture cycle.

Model:

Purpose:

- Ray tracing program created to determine if the focused light from M2 is falling onto the RCWS both fore and aft of the focus.
- Determine amount of tip and tilt can be achieved on M2 with the selected linear traverse.
- Determine required translation of RCWS linear traverse.

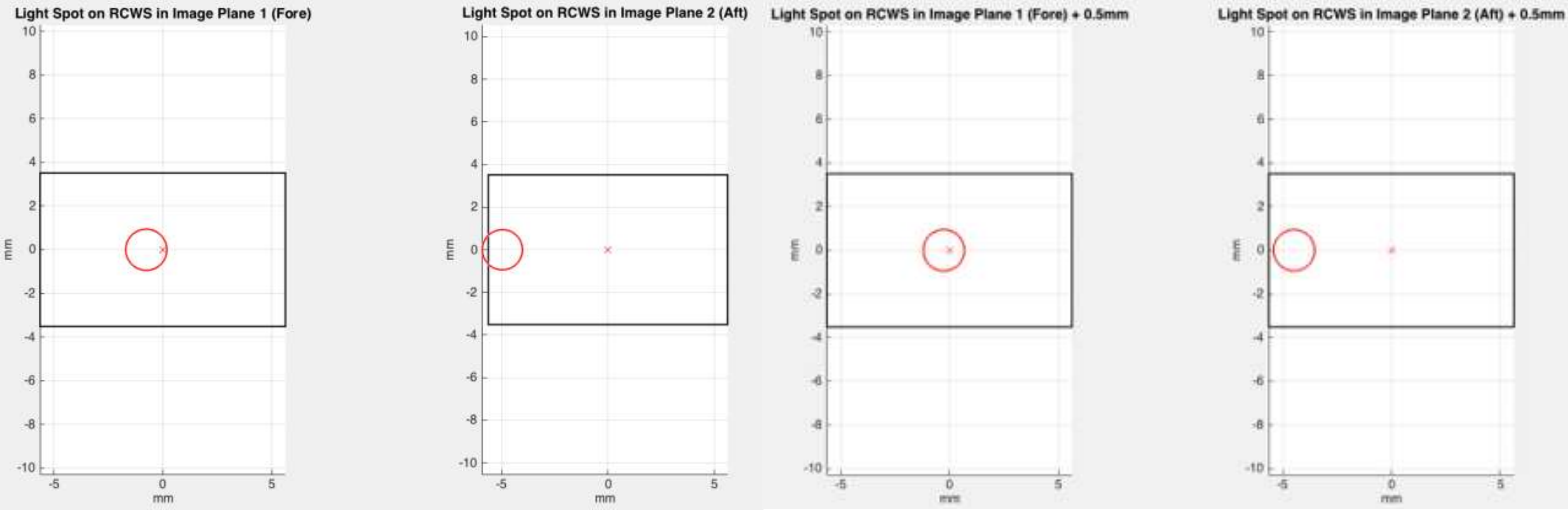
Limitations:

- Breaks down at large tip/tilt angles.
- 1 degree of freedom, so either tip or tilt, not both.

Assumptions:

- Image on RCWS is always circular.
- Image occurs only within the optical cone.
- RCWS traverse is aligned with the optical axis of perfectly-aligned M2.

3.9/4.9 - Detector Image Spill



Light Spot on RCWS in Image Plane 1 (Fore)

Light Spot on RCWS in Image Plane 2 (Aft)

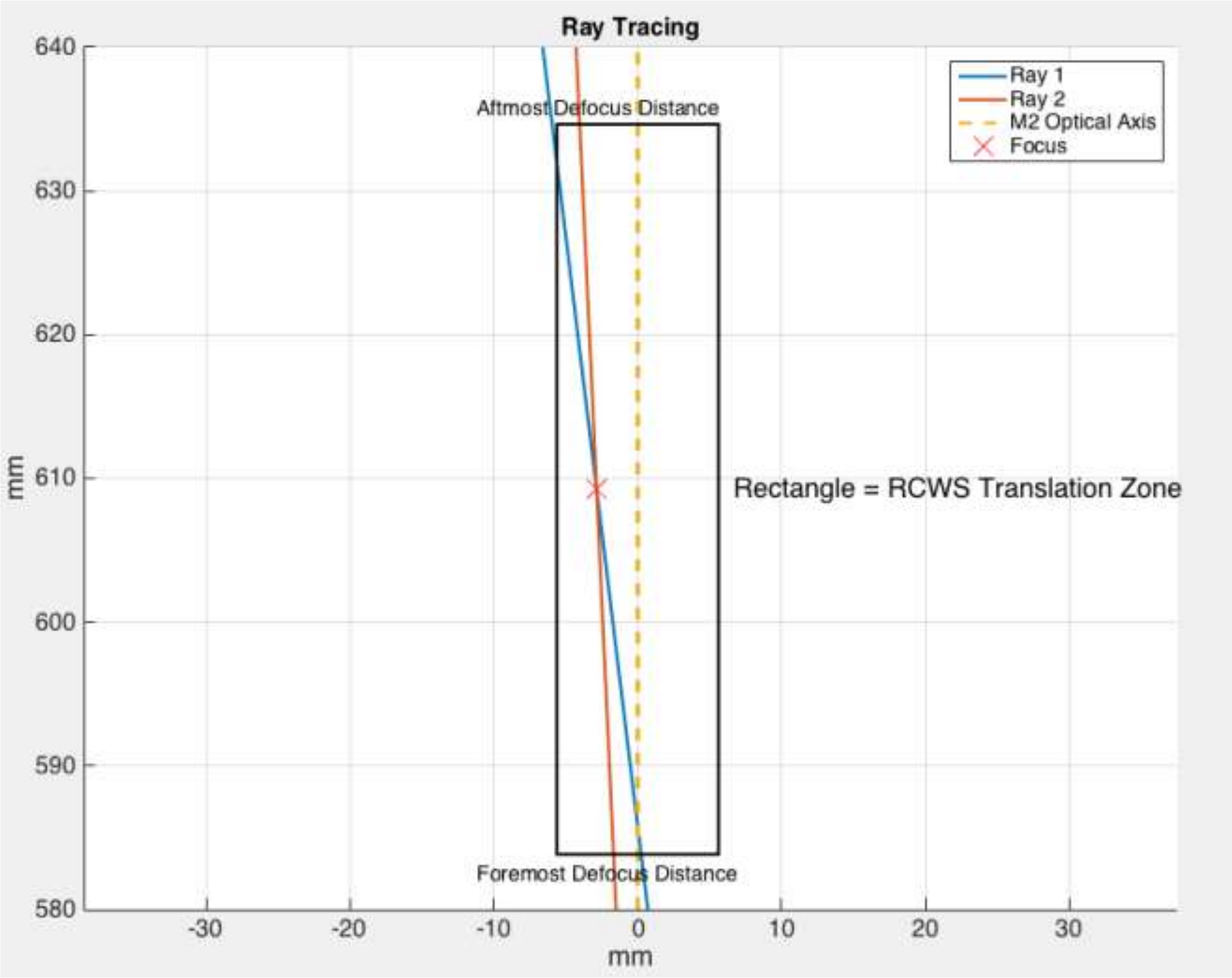
Light Spot on RCWS in Image Plane 1 (Fore) + 0.5mm

Light Spot on RCWS in Image Plane 2 (Aft) + 0.5mm

- Result: The leftmost plots represent the image spots on the RCWS with no offset from M2 optical axis. With an adjustment of 0.5mm of the RCWS translational plane, the image can be shifted to be entirely on the RCWS.

3.9/4.9 - Detector Image Spill

RCWS Ray Tracing - Top View



- Top View showing possible range of the RCWS translational stage. Shown with M2 tilt = 0.135 degree.

3.10/4.10 - RCWS Interpretation Algorithm

Critical Factor:

- The RCWS algorithm must produce Zernike polynomials from image data.

Model:

Purpose:

- Calculate Zernike Coefficients from RCWS intensity matrix output.

Assumptions:

- The RCWS defocused to the commanded defocus distance
- Auxiliary light sources are negligible.

Limitations:

- As the defocus distance becomes too large, the blur decreases the image resolution.
- As the defocus distance becomes too small, the number of intensity values yielded are not sufficient to calculate higher order Zernike Coefficients.

3.10/4.10 - RCWS Interpretation Algorithm

- Previously generated images were converted into arrays of intensity values.

- These intensity values were then run through the RCWS interpretation algorithm to see if the same Zernike Coefficients were produced.

```
Z  1     -0.08973651  :        1
Z  2      0.00000000  :         4^(1/2) (p) * COS (A)
Z  3     -0.00018355  :         4^(1/2) (p) * SIN (A)
Z  4     -0.05178935  :         3^(1/2) (2p^2 - 1)
Z  5      0.00000000  :         6^(1/2) (p^2) * SIN (2A)
Z  6      0.00000026  :         6^(1/2) (p^2) * COS (2A)
Z  7     -0.00006484  :         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      0.00001553  :         5^(1/2) (6p^4 - 6p^2 + 1)
```

This RCWS interpretation algorithm depends on the Poisson Equation:

$$\frac{\partial I}{\partial z} = \frac{\lambda F(F-l)}{2\pi l}\left[\frac{\partial}{\partial n}\phi\left(\frac{F\vec{r}}{l}\right)\delta_c - \nabla^2\phi\left(\frac{F\vec{r}}{l}\right)\right]$$

This is difficult to solve, and two main methods for doing so:

- FFT Method
- Zernike Matrix Method

3.11/4.11 - Zernike Amplitude to Defocused Image Model

Critical Factor:

- Independently validate Zernikes produced by RCWS algorithm.
- Potentially the assumption that the SHA gives "truth" could be refuted if RCWS and forward predictive model results match despite disagreement between SHA and RCWS.
- Provide increased confidence when observing defocused images in experiment.

Model:

Purpose:

- Simulate RCWS Images solely from Zernike polynomials.
- Validate the Zernikes produced by the RCWS system.
- Verifying the wavefront errors we are introducing will be detectable by image sensors.

Assumptions:

- Zemax produces correct Zernike coefficients.

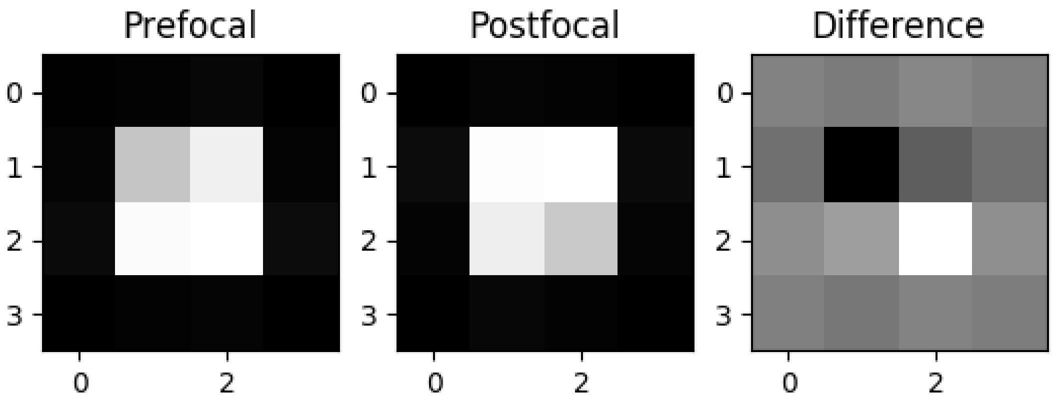
Limitations:

- PROPER limits how small the RCWS defocus distance can be.
- Dependent on the resolution of the CMOS being modeled.

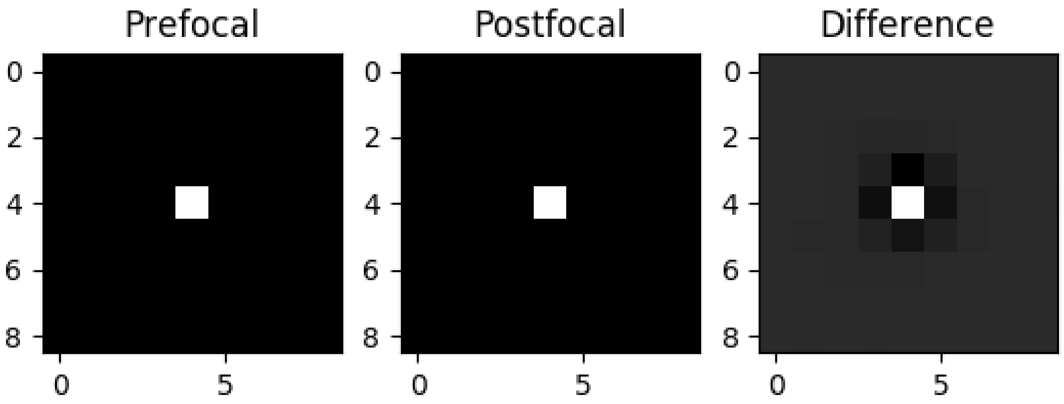
3.11/4.11 - Zernike Amplitude to Defocused Image Model

- Example output at very small defocus distance.
  - Few pixels illuminated
  - Differences in intensity are large

Tilt: 1 degree
Defocus: 100 micrometers



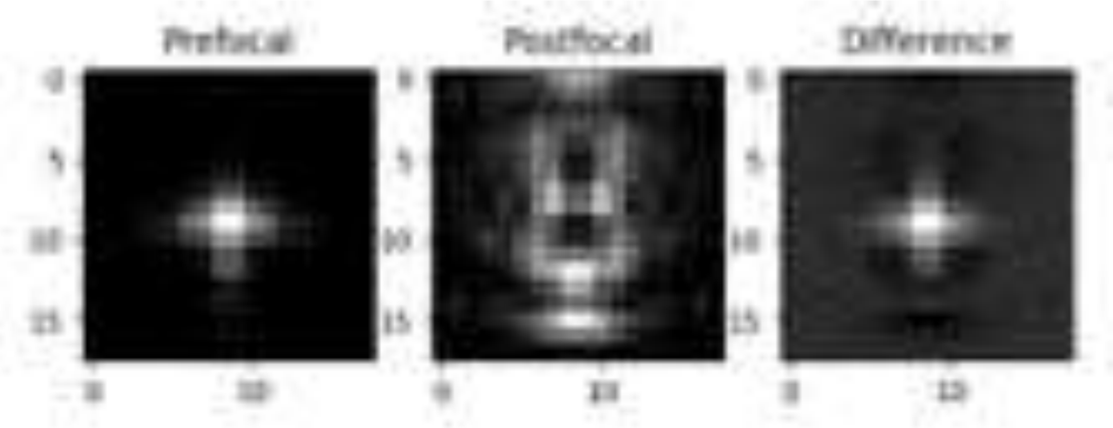
Tilt: 1 degree
Defocus: 200 micrometers



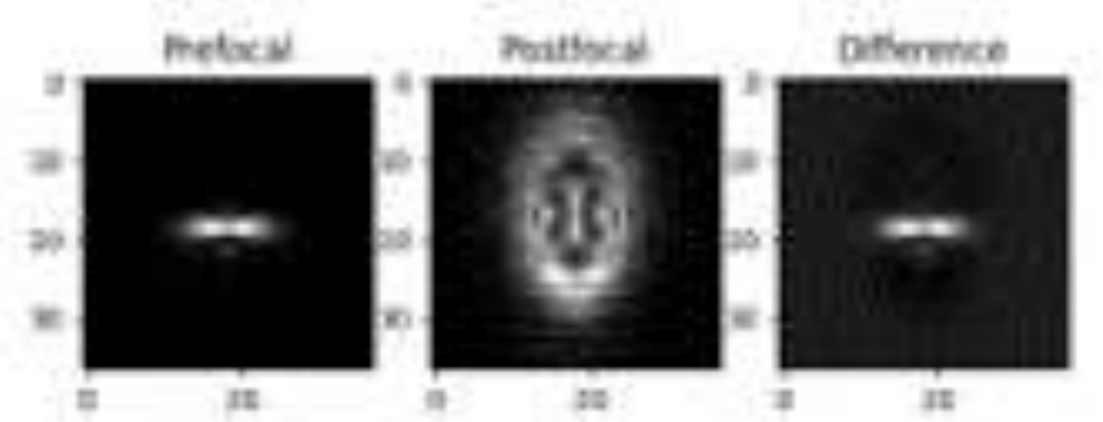
3.11/4.11 - Zernike Amplitude to Defocused Image Model

- Example output at mid defocus distance.
  - More pixels illuminated for more data points.
  - Differences in intensity are less, potentially increasing error in determining Zernike amplitudes

Tilt: 1 degree
Defocus: 400 micrometers

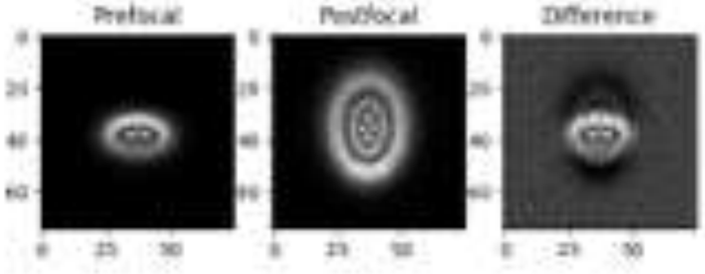


Tilt: 1 degree
Defocus: 800 micrometers

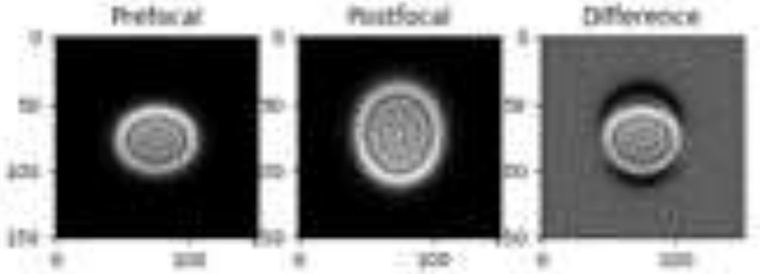


3.11/4.11 - Zernike Amplitude to Defocused Image Model

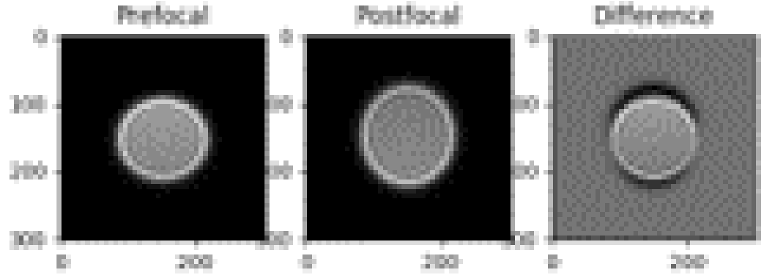
Tilt: 1 degree
Defocus: 1600 micrometers



Tilt: 1 degree
Defocus: 3200 micrometers



Tilt: 1 degree
Defocus: 6400 micrometers



3.12/4.12 - Testbed Thermal Model

Critical Factor:

- Thermal effects may deform the optical system thereby introducing wavefront error that decreases the SNR. Minimum resolution of temperature data to avoid such errors will be determined.

Model:

Purpose:

- Identify significant sources of error or changes to optical path due to thermal effects
- Quantify the changes in testbed alignment due to thermal expansion

Assumptions:

- 2-D thermal expansion is sufficient
- Y-direction expansion insignificant
- Solid aluminum of uniform coefficient of thermal expansion of 23.6 µm / (m K) @ room temperature
- Main source of heat is surrounding air
    - Image source location is remote to table

$$\Delta A = A\alpha\Delta T$$

A = relevant breadboard area
α = coef. of planar thermal expansion
T = temperature

Table 1: Change in Strehl ratio due to elongation in Z-axis

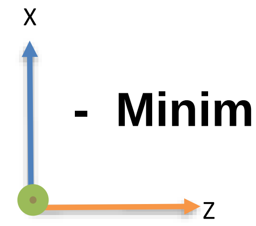
	Image Source -> M1	M2 -> Sensors
dS/dz	0.4735/mm	0.2440/mm

Results

- A ΔT of 1.414K, the expansion creates a 1% change in Strehl ratio

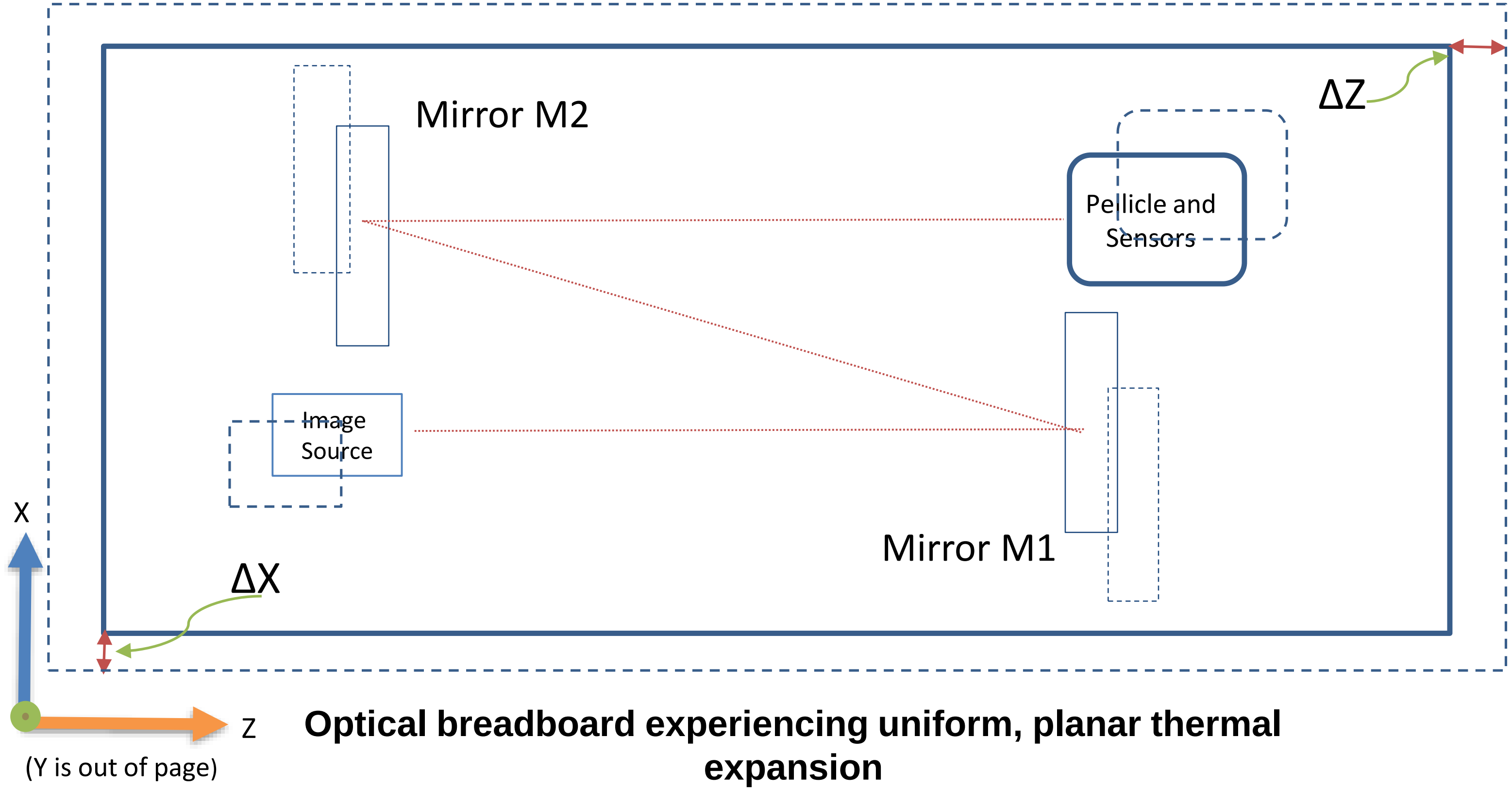
- Each 1K change in temperature causes a ΔZ of 8.87µm, and a ΔX of 3.70µm

- Minimum accuracy of temp. sensors = ±1.0K



(Y is out of page)

3.12/4.12 - Testbed Thermal Model



Optical breadboard experiencing uniform, planar thermal expansion

- Increase in temperature of breadboard (chiefly due to surrounding air) causes uniform expansion of the table.
- From the Zemax model used to validate the optical system: Overall elongation/contraction of all or some parts of the optical path results in change to the Strehl ratio
  - This change is negative if the path expands, and vice versa

3.13/4.13 - Testbed Vibrational Model

Critical Factor:

- Vibrations present on optical components cause displacements that introduce noise in wavefront measurements.
- Understanding the nature of these vibrations informs the environmental sensor system of necessary sensor resolution and placement, as well as test invalidating conditions.

Model:

Purpose:

- Model movement of the mirrors with respect to forcing function applied to the optical table
- Used to determine the maximum allowable forcing that can occur during a test while maintaining acceptable errors
- Could predict settling time of the system if damping terms could be estimated
- Could be used to predict the measurements made by accelerometers
- Can predict "initial condition" response without an input force

Assumptions:

- Only the two mirrors move because they are tall and massive
- No slop in mounting hardware considered
- The mirror and mount behind the mirror are rigid bodies
- The mount below the mirror acts as a torsional spring

3.13/4.13 - Testbed Vibrational Model

$$\begin{bmatrix} \dot{\theta}_Y \\ \ddot{\theta}_Y \\ \dot{\theta}_Z \\ \ddot{\theta}_Z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-k_Y}{I_Y} & \frac{-d_Y}{I_Y} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{-k_Z}{I_Z} & \frac{-d_Z}{I_Z} \end{bmatrix} \begin{bmatrix} \theta_Y \\ \dot{\theta}_Y \\ \theta_Z \\ \dot{\theta}_Z \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & R \\ 0 & 0 \\ -R & 0 \end{bmatrix} \begin{bmatrix} F_Y(t) \\ F_Z(t) \end{bmatrix}$$

Limitations:

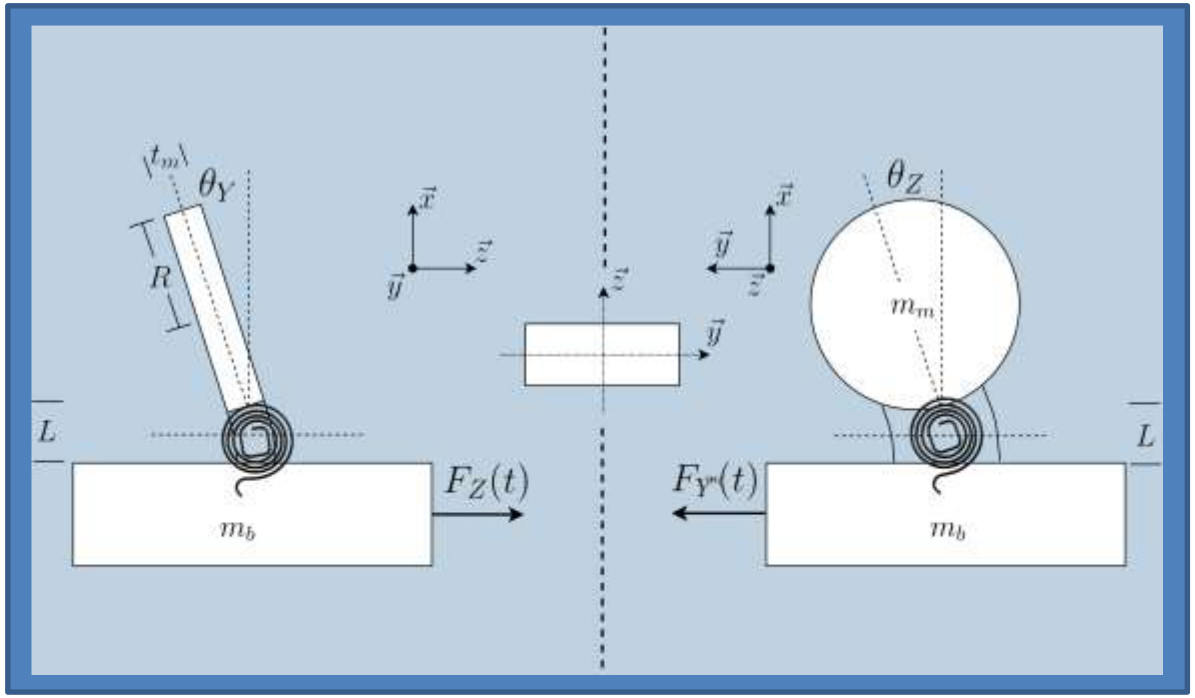
- Does not consider effects of vibration on other components and damping terms are assumed
- Only Strehl effects modelled, not effects on Zernike amplitudes

$$I_Y = \frac{m}{12}(3R^2 + t^2) + mR^2 \quad K_Z = \frac{EI_{area,Z}}{L}$$

$$I_Z = \frac{m}{2}R^2 + mR^2 \quad K_Y = \frac{EI_{area,Y}}{L}$$

$$S = 1 - dS$$

$$dS = \begin{bmatrix} 1.5579 & 0.1437 \end{bmatrix} \begin{bmatrix} \theta_Y \\ \theta_Z \end{bmatrix}$$



3.13/4.13 - Testbed Vibrational Model

Test Conditions

Variable	Value
E [GPa]	69
$I_{area,Y}$ $[m^4 \cdot 10^{-7}]$	0.14
$I_{area,Z}$ $[m^4 \cdot 10^{-7}]$	2.22
L [m]	0.0254
R [m]	0.0762
t [m]	0.0254
m [kg]	1.25

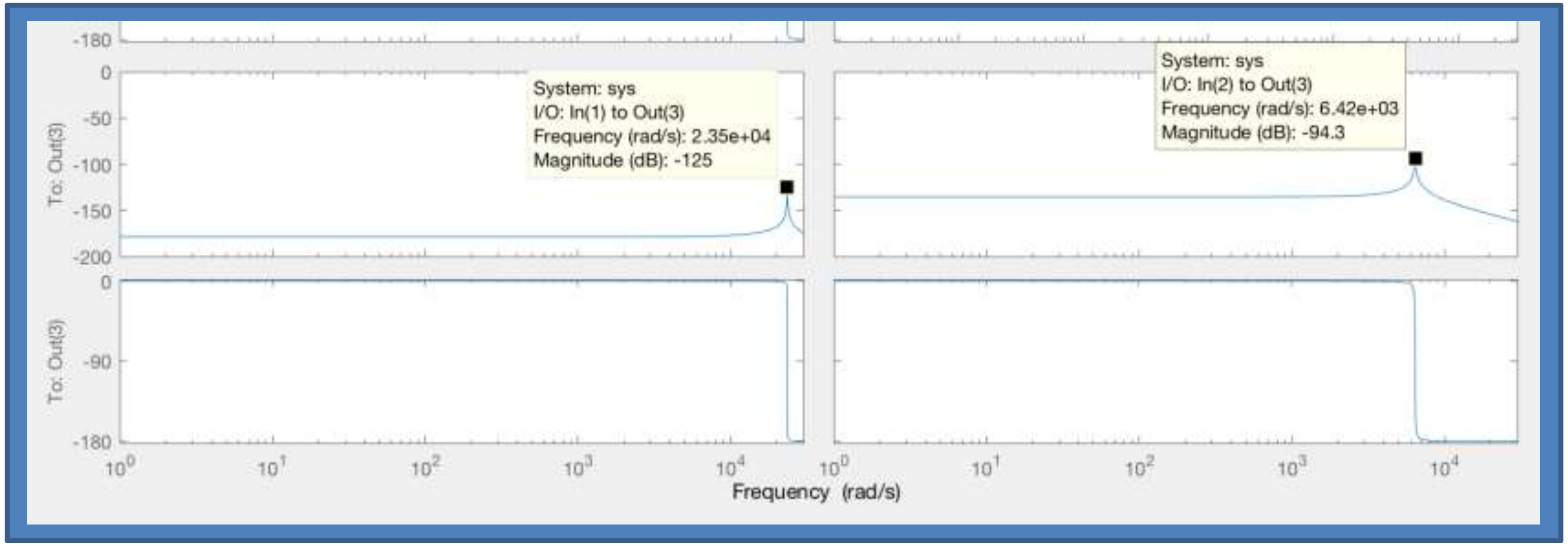
Results

Variable	Value, Y	Value, Z
$\omega_{n,Y}$ [rad/s]	$6.42 \cdot 10^3$	$23.5 \cdot 10^3$
$G(\omega = 0)$ $[\frac{rad}{N}]$	-175	-197
$G(\omega = 1885)$ $[\frac{rad}{N}]$	-174	-197

Conclusions:

- Unlikely to see harmonic forcing of the system
- Gain in Strehl ratio change is small so vibration is not expected to be a significant factor in wavefront error noise levels
- The model is likely inappropriate due to lack of modelling damping effects of slop in system

Frequency gain response of change in Strehl ratio



3.14/4.14 - Sensor + Teensy Timing Model

Critical Factors:

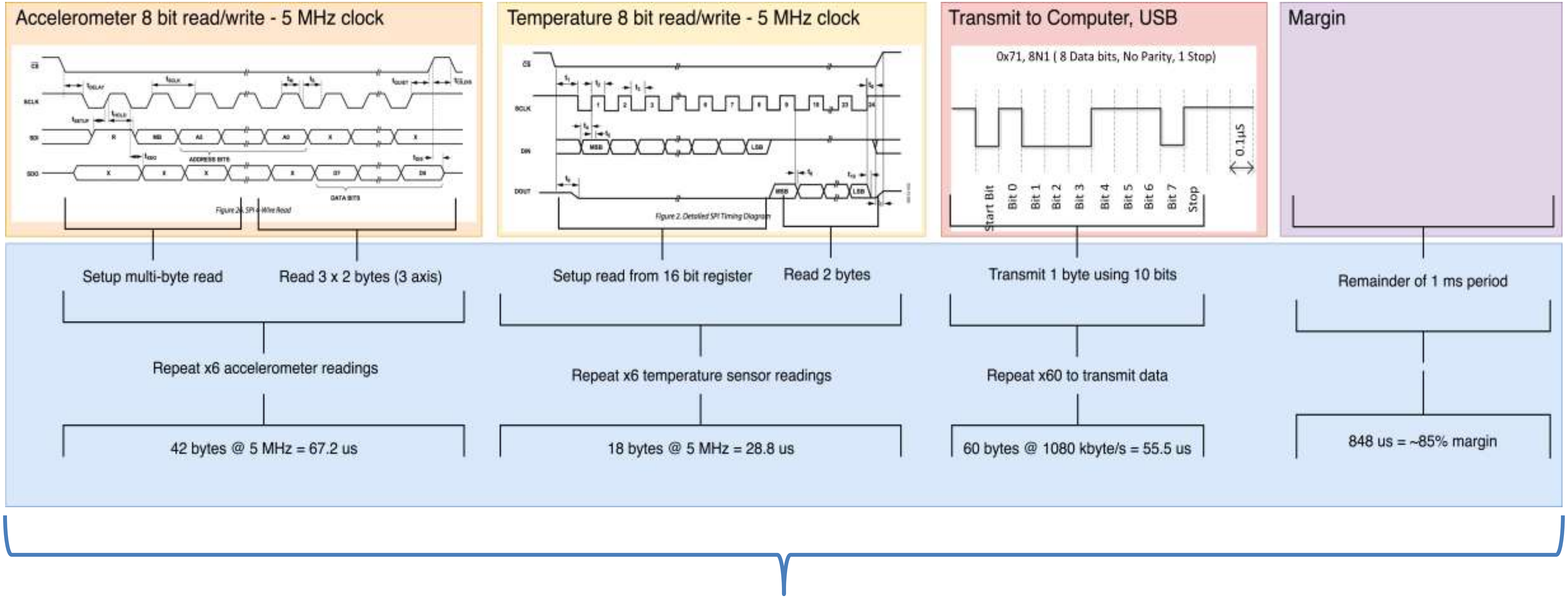
In order to meet the customer's requirement to sense up to 300 Hz vibrations the system must transmit data at 1000 Hz. It is important to ensure that this rate is attainable with reasonable margin to allow the microcontroller to handle other necessary tasks.

Results:

- Worst case (temperature + acceleration reading) cycle time must be within 1ms requirement
- Fraction of cycle time spent sampling from sensors – 10%
- Fraction of cycle time spent transmitting data to the computer – 5%
- 85 percent margin allows for necessary operations such as changing slave devices, sending framing bytes, and performing computations with the microcontroller

Model details on following slide

3.14/4.14 - Sensor + Teensy Timing Model



Accelerometer 8 bit read/write - 5 MHz clock

Setup multi-byte read

Read 3 x 2 bytes (3 axis)

Repeat x6 accelerometer readings

42 bytes @ 5 MHz = 67.2 us

Temperature 8 bit read/write - 5 MHz clock

Setup read from 16 bit register

Read 2 bytes

Repeat x6 temperature sensor readings

18 bytes @ 5 MHz = 28.8 us

Transmit to Computer, USB

Transmit 1 byte using 10 bits

Repeat x60 to transmit data

60 bytes @ 1080 kbyte/s = 55.5 us

Margin

Remainder of 1 ms period

848 us = ~85% margin

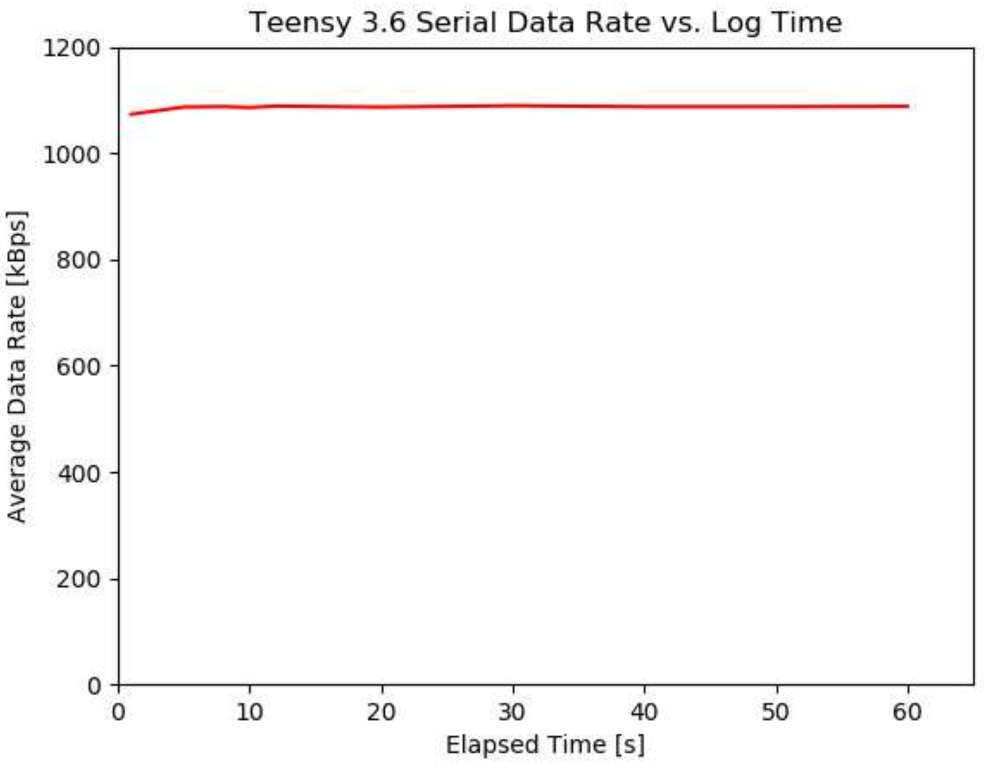
Total period sums to 1 ms for
1000 Hz sampling frequency

3.15/4.15 - Data Rate Testing

- Serial Read Data Rates were constructed using Python with pyserial, Windows 10, and a Teensy 3.6.
- For Data checking, the Teensy had been set to count from 0 to 99 endlessly while streaming the data over serial. The data was detected to have zero errors.
- Tests were run with varying time intervals of 1, 5, 8, 10, 12, 20, 30, 40, 50, and 60s

Serial Testing Results			
Average Data Rate: [kBps]	Total Number of Bytes Sent	Total Time Taken: [s]	Tests Conducted:
1086.041	256754500	236.066	10

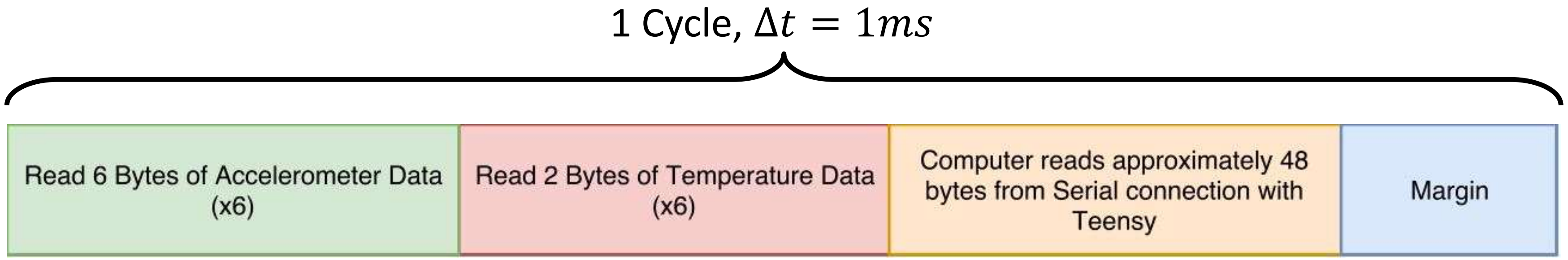
Generic SPI Device Testing Results			
Average Switching Time [µs]	Average 48-bit Read Time [µs]	Total Number of Switches and Reads	Tests Conducted
0.5104	12.976	465572	10



- SPI testing was completed with two generic accelerometers, testing read time and the time required to switch between sensors

3.15/4.15 - Data Cycle Test

Actual System Cycle:



1 Cycle, $\Delta t = 1ms$

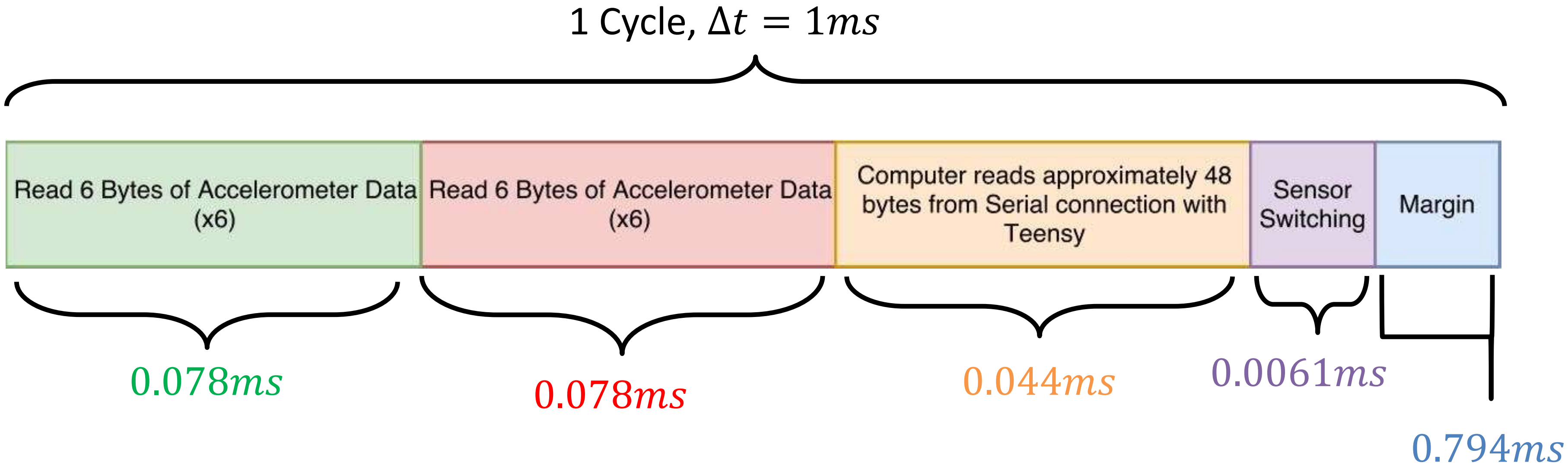
Read 6 Bytes of Accelerometer Data (x6)

Read 2 Bytes of Temperature Data (x6)

Computer reads approximately 48 bytes from Serial connection with Teensy

Margin

Previously Tested / Simulated Cycle:



1 Cycle, $\Delta t = 1ms$

Read 6 Bytes of Accelerometer Data (x6)

Read 6 Bytes of Accelerometer Data (x6)

Computer reads approximately 48 bytes from Serial connection with Teensy

Sensor Switching

Margin

$0.078ms$

$0.078ms$

$0.044ms$

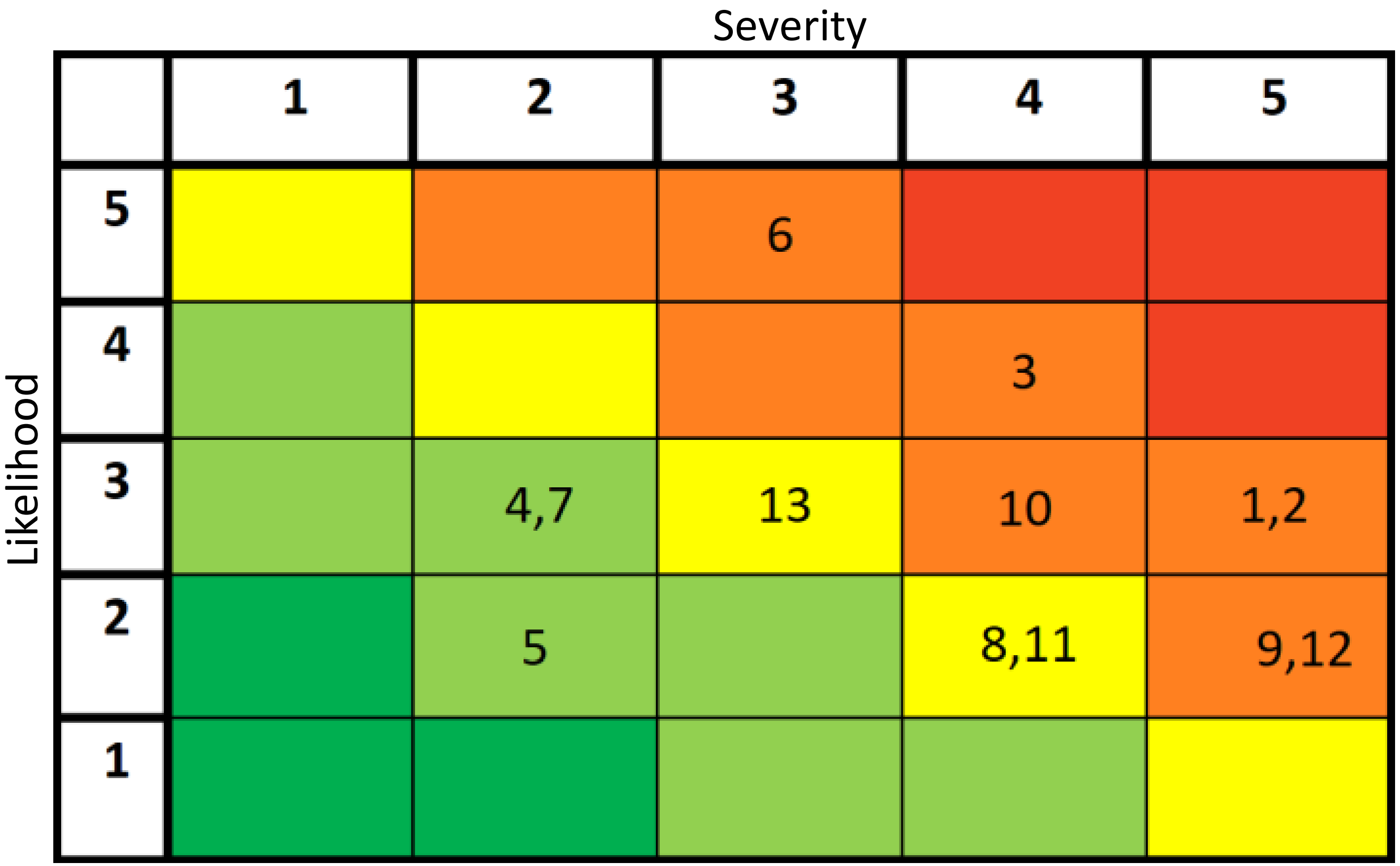
$0.0061ms$

$0.794ms$

5.0 PROJECT RISKS

5.1 - Risk Analysis

Pre-Mitigation Risk Analysis



Severity

Likelihood

	1	2	3	4	5
5			6		
4				3	
3		4,7	13	10	1,2
2		5		8,11	9,12
1					

- **1.** Testbed not aligned correctly
- **2.** Algorithm does not correctly convert RCWS images into Zernike Polynomials
- **3.** Dust/fingerprints/damage introduced to optical components
- **6.** Non-consistent thermal and vibrational effects create inconsistent results

5.1 - Risk Analysis

- **Risk 1: Testbed not aligned correctly**

- **Severity:** 5 **Likelihood:** 3 **Total:** 15
- **Description:** Testbed may not align correctly, producing unintended errors in the wavefront measurement and overall failure of our project
- **Mitigation options:**
  - Large amount of time spent planning and 3D modeling before system is built
  - Write a detailed alignment procedure
  - Careful assembly of the entire system according to plan
- **Response if risk occurs:**
  - Realign the system
  - Look into alignment measurement devices

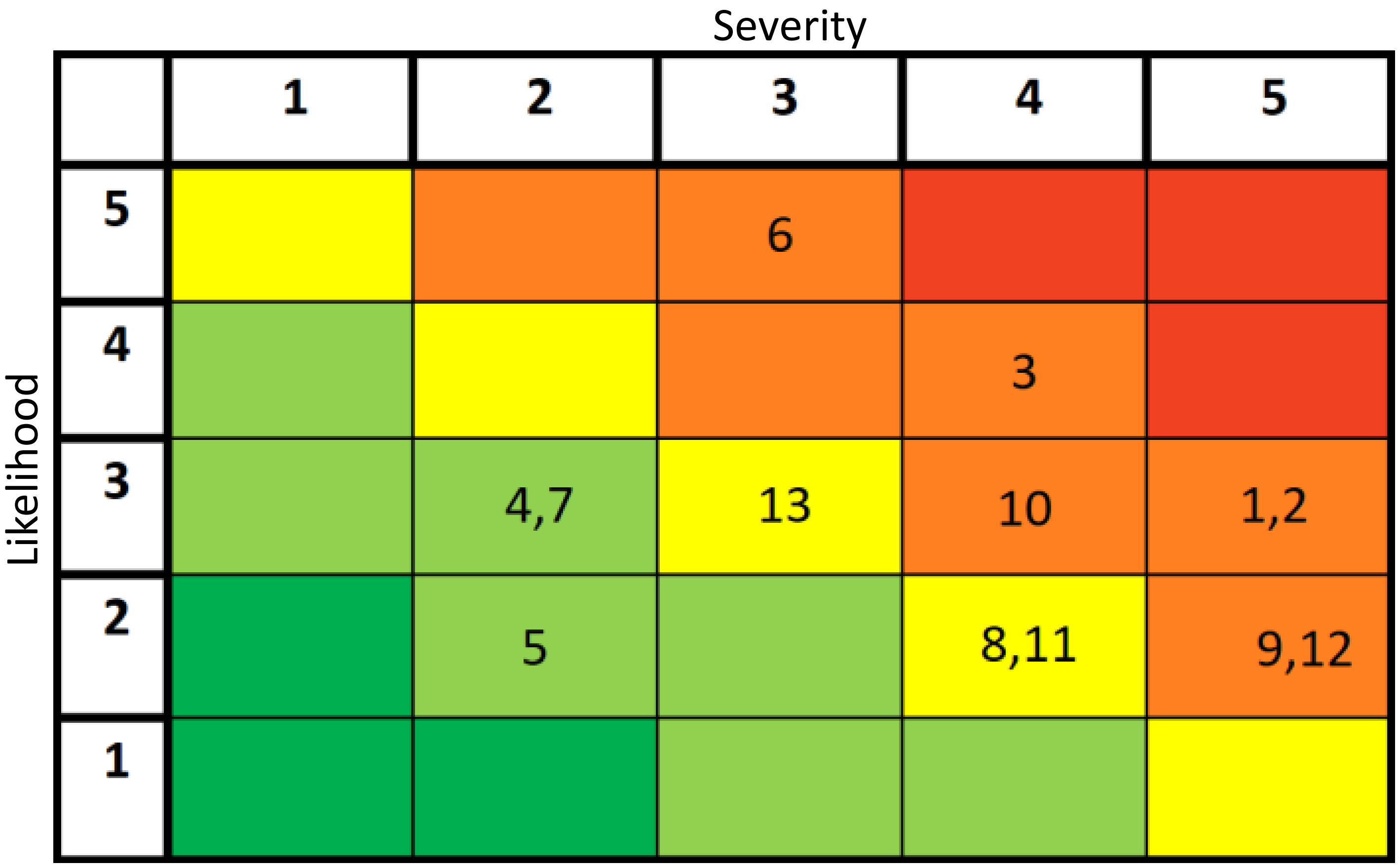
Post Mitigation Risk Analysis

- **Severity:** 5 **Likelihood:** 2 **Total:** 10

Other risks detailed in back-up slides

5.1 - Risk Analysis

Pre-Mitigation Risk Analysis



Severity

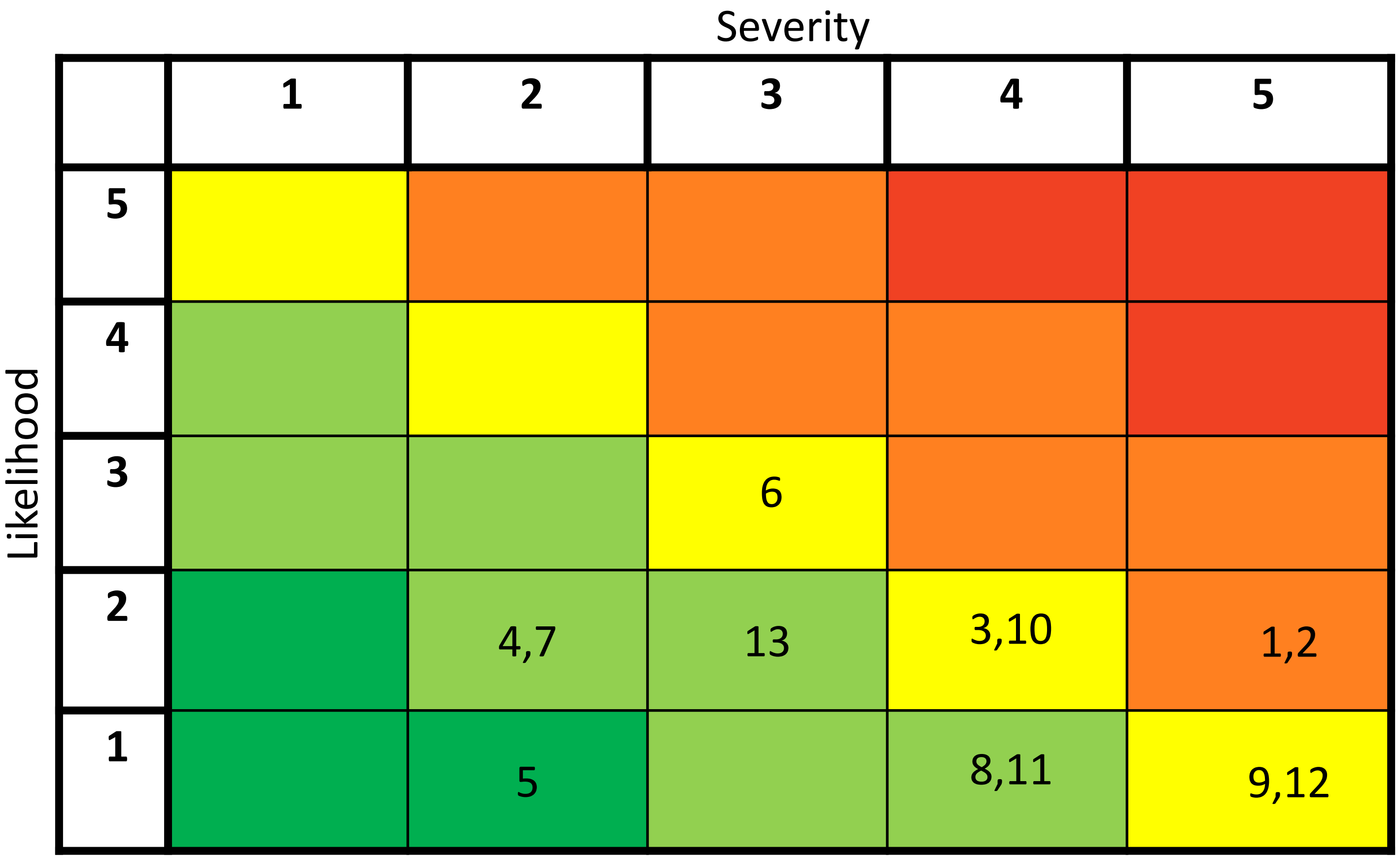
Likelihood

	1	2	3	4	5
5			6		
4				3	
3		4,7	13	10	1,2
2		5		8,11	9,12
1					

- **1.** Testbed not aligned correctly
- **2.** Algorithm does not correctly convert RCWS images into Zernike Polynomials
- **3.** Dust/fingerprints/damage introduced to optical components
- **6.** Non-consistent thermal and vibrational effects create inconsistent results

5.1 - Risk Analysis

Post-Mitigation Risk Analysis



Severity

Likelihood

	1	2	3	4	5
5					
4					
3			6		
2		4,7	13	3,10	1,2
1		5		8,11	9,12

- **1.** Testbed not aligned correctly
- **2.** Algorithm does not correctly convert RCWS images into Zernike Polynomials
- **3.** Dust/fingerprints/damage introduced to optical components
- **6.** Non-consistent thermal and vibrational effects create inconsistent results

6. VERIFICATION AND VALIDATION

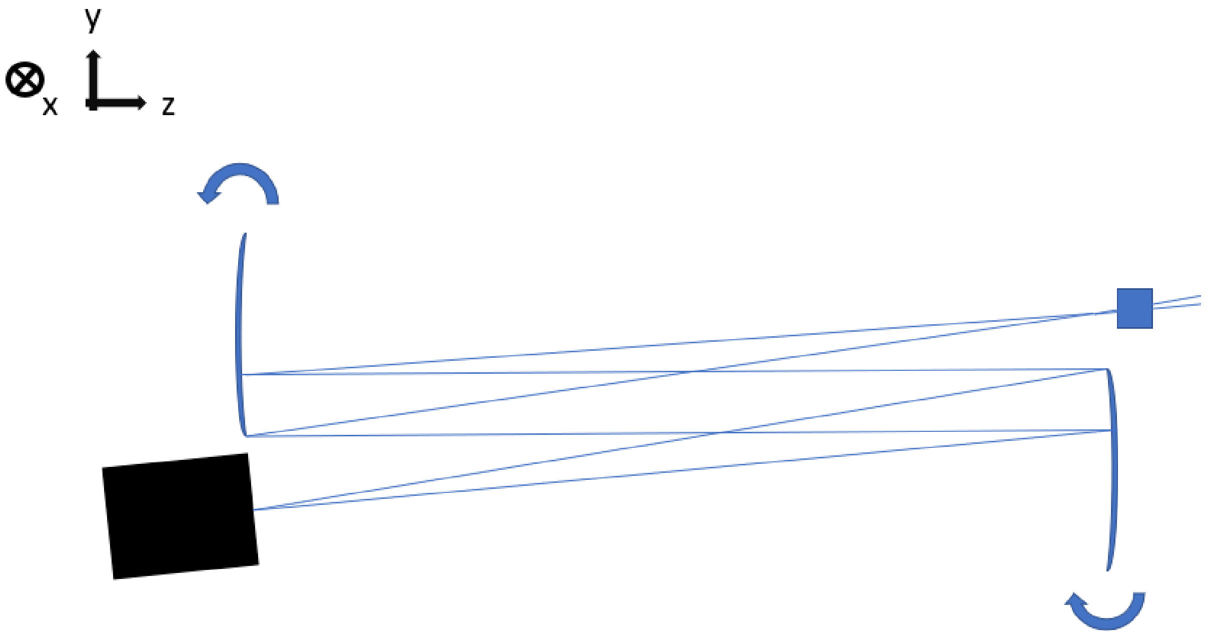
6.1 - Optical Alignment Sensitivity

Purpose: Validate optical alignment sensitivities on Zernikes given by the optical path model in Zemax.

Equipment: All optical components, image source, SHA, shroud, PC

Location: SwRI Lab

Dark Room Required? Yes



Tasks:
- Change orientations of M1 to check sensitivities of M1 misalignment on Zernikes
- Change orientations of M2 to check sensitivities of M2 misalignments on Zernikes

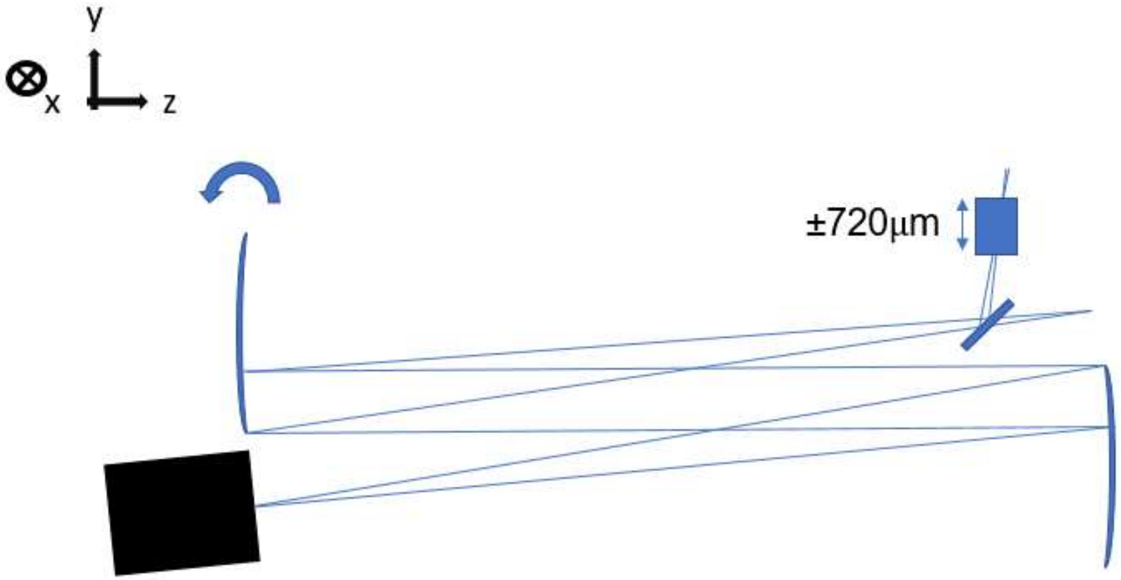
6.2 - RCWS Imagery

Purpose: Validate RCWS defocus locations are proper with no spillage and enough capture area to calculate Zernikes.

Equipment: All optical components, image source, RCWS, shroud, PC

Location: SwRI Lab

Dark Room Required? Yes



Tasks:

- Produce RCWS imagery at fore- and aft-focus positions for initial and final experimental rotary positions of M2
- Check for spillage and that software can produce Zernikes

6.3 - Wavefront Sensor Read-out Noise

Purpose: Determine baseline noise levels of the RCWS and SHA within the shroud.

Equipment: SHA, RCWS, shroud, PC

Location: SwRI Lab

Dark Room Required? Yes

Tasks:

- Conduct zero-light tests within the shroud with varied exposure times for all seven octaves of light capture

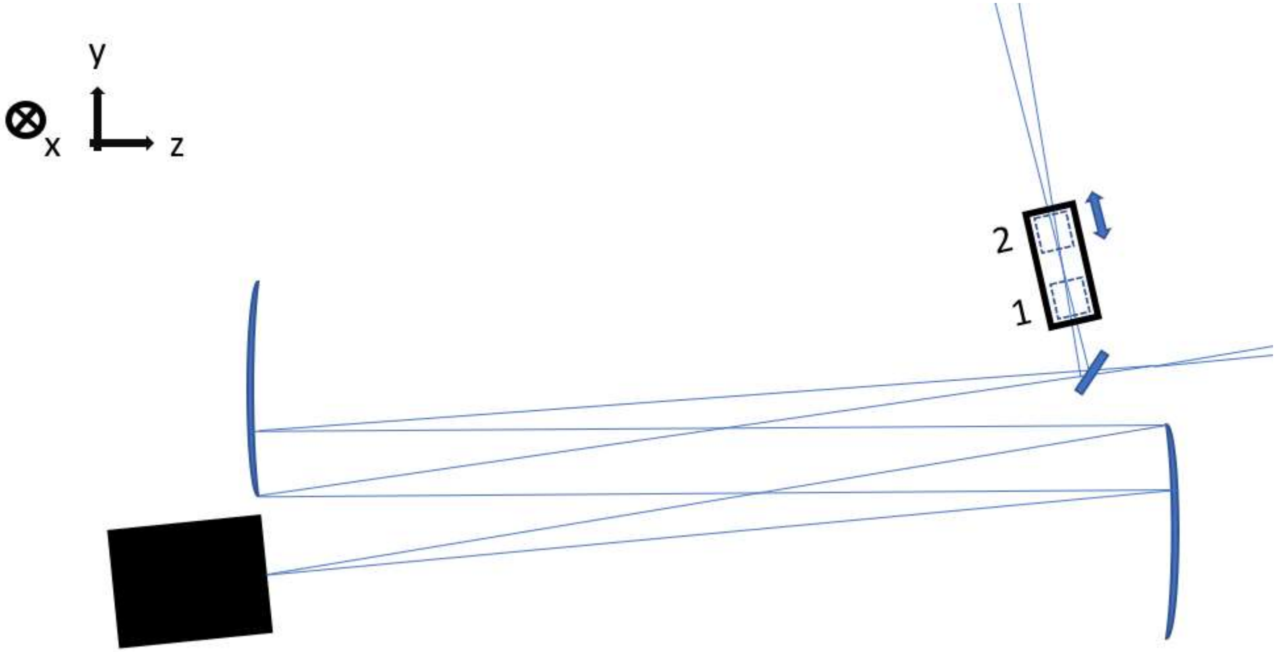
6.4 - RCWS Defocus Sensitivity

Purpose: Characterize sensitivity of Zernike read-out to non-ideal RCWS defocus.

Equipment: All optical components, RCWS, shroud, PC

Location: SwRI Lab

Dark Room Required? Yes



Tasks:
- Produce initial fore-focus image from RCWS
- Produce Zernike sensitivities to non-ideal aft-focus position imagery
- Compare to forward-predictive model

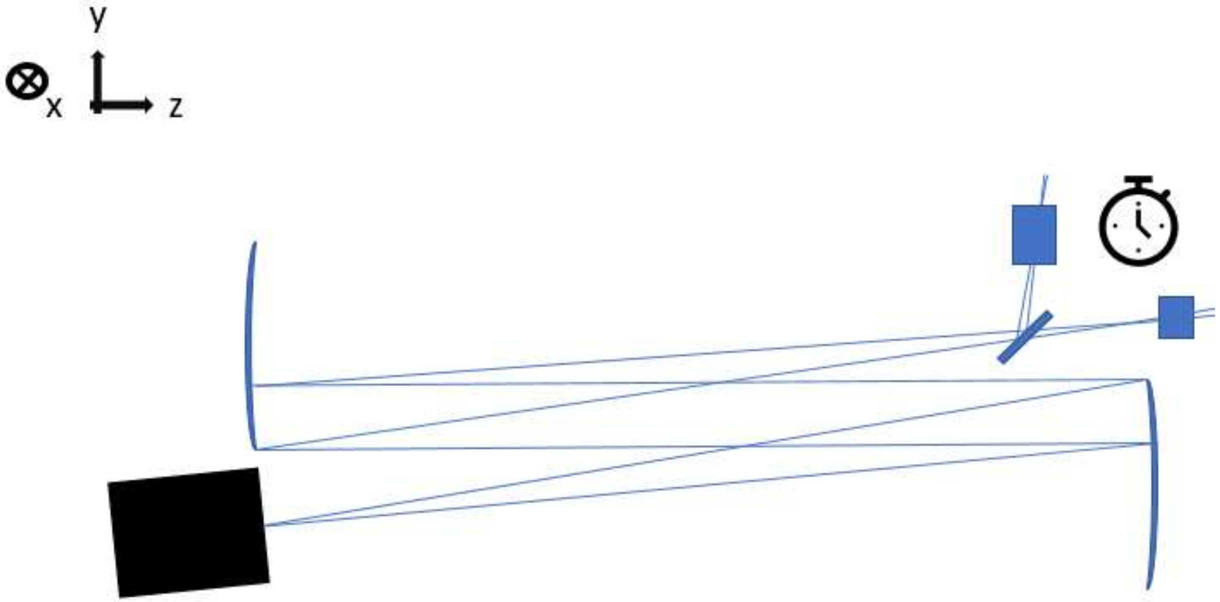
6.5 - Power to Wavefront Sensors

Purpose: Characterize exposure effect on signal to ensure power requirement.

Equipment: All optical components, RCWS, SHA, image source, shroud, PC

Location: SwRI Lab

Dark Room Required? Yes



Tasks:

- Vary exposure times from RCWS and SHA to determine saturation cap (if reached) and characterize signal curve with respect to exposure

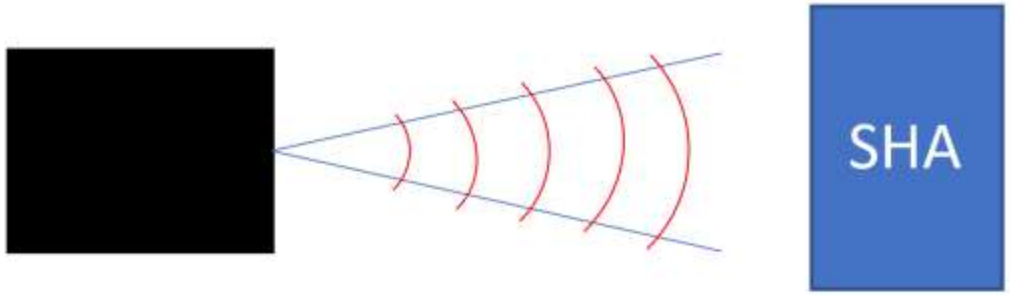
6.6 - Post-Pinhole Wavefront

Purpose: Determine if the wavefront post-pinhole is spherical.

Equipment: Image source, shroud, PC

Location: SwRI Lab

Dark Room Required? Yes



Tasks:

- Produce SHA imagery and calculate Zernikes to validate spherical wavefront post-pinhole

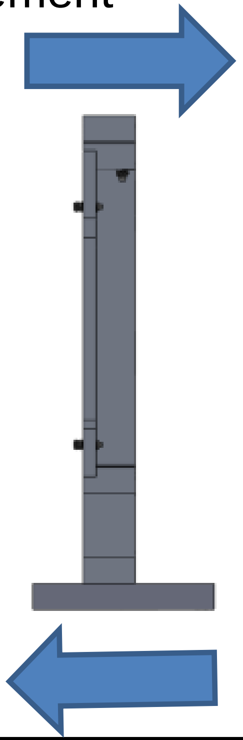
6.7 - Vibrational Effects

Purpose: Obtain more accurate information about component vibrational responses.

Equipment: Mirror mounts, sensor mounts, shaker table, accelerometers, shroud, PC

Location: ECAE Basement

Dark Room Required? No



Tasks:

- Measure differential accelerations between top and bottom of each mount on shaker table
- Apply several different forcing's to retrieve a curve on the max deflection effects

6.8 - Environmental Sensor Performance

Purpose: Validate the performance of the environmental sensors.

Equipment: Temperature sensors, accelerometers, PC

Location: ECAE Basement **Dark Room Required?** No

Tasks:

- Check operability of 12 sensors by running for three hours
- Check operability of Teensy 3.6 with timing and loading with 12 sensors

7. PROJECT PLANNING

7.1 - Organizational Chart

Project Customer:
Eliot Young
SwRI

Optics Consultant:
Bob Woodruff

Owen Lyke
Project Manager

Brandon Stetler
Systems Engineer

Lucas Droste
Manufacturing
Financial Lead

Ali Colic
Safety Lead
Thermal Lead

Brandon Noirot
Test Lead

Owen Shepherd
Environmental Sensor Lead

Diego Gomes
Image Source Lead

Ankit Hriday
Optical Path Lead

Robert Belter
Algorithm Lead
Software Lead

Jake Crouse
Image Sensor Lead

7.2 - Work Breakdown Structure

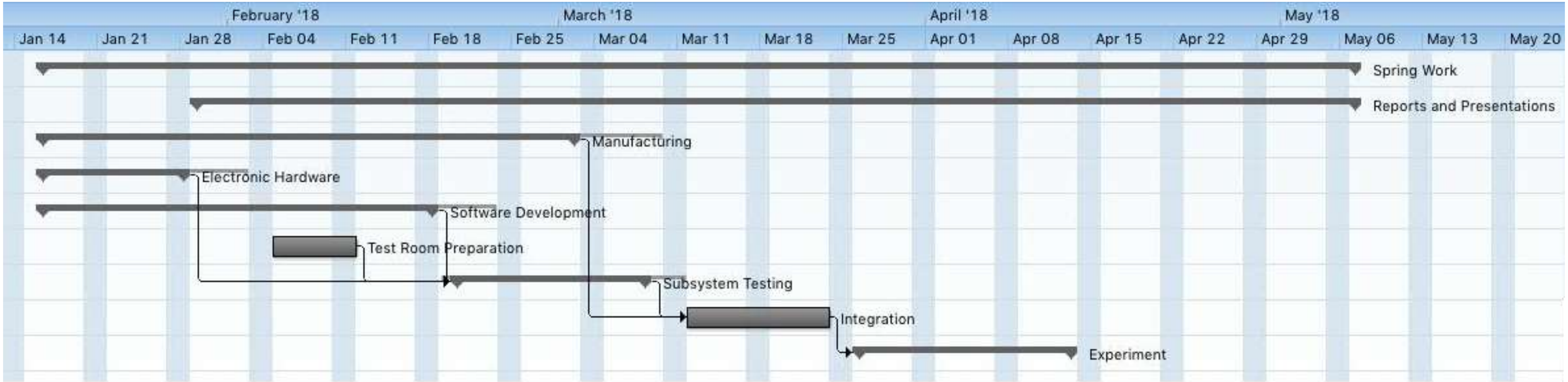
AWESoMe

- Procurement
  - 🟩 Create Bill of Materials
  - 🟩 Obtain Procurement Card
  - 🟥 Purchase Raw Materials
  - 🟥 Purchase COTS Optical Components
- Manufacturing
  - 🟩 Design Mounts and Brackets
  - 🟩 Tolerance Analysis
  - 🟥 Machine Components
  - 🟥 Assembled Structure
- Algorithms and Software
  - 🟩 Forward-Predictive Model
  - 🟥 Back-Predictive Model
  - 🟥 Test individually with stages and RCWS
  - 🟥 Scale and test interfacing code
- Environmental Sensors
  - 🟩 Determine preferred sensors
  - 🟩 Choose microcontroller and sensors
  - 🟩 Basic sensor interfacing and code
  - 🟥 Computer-side CLI logging program
  - 🟥 Scale / Test MCU code for 12 sensors
  - 🟥 IC and PCB Soldering
  - 🟥 Mounting
- Deliverables
  - 🟩 PDD
  - 🟩 CDD
  - 🟩 PDR
  - 🟩 EEF Proposal
  - 🟩 CDR
  - 🟥 FFR
  - 🟥 MSR
  - 🟥 TRR
  - 🟥 SRF
  - 🟥 SWRI Paper

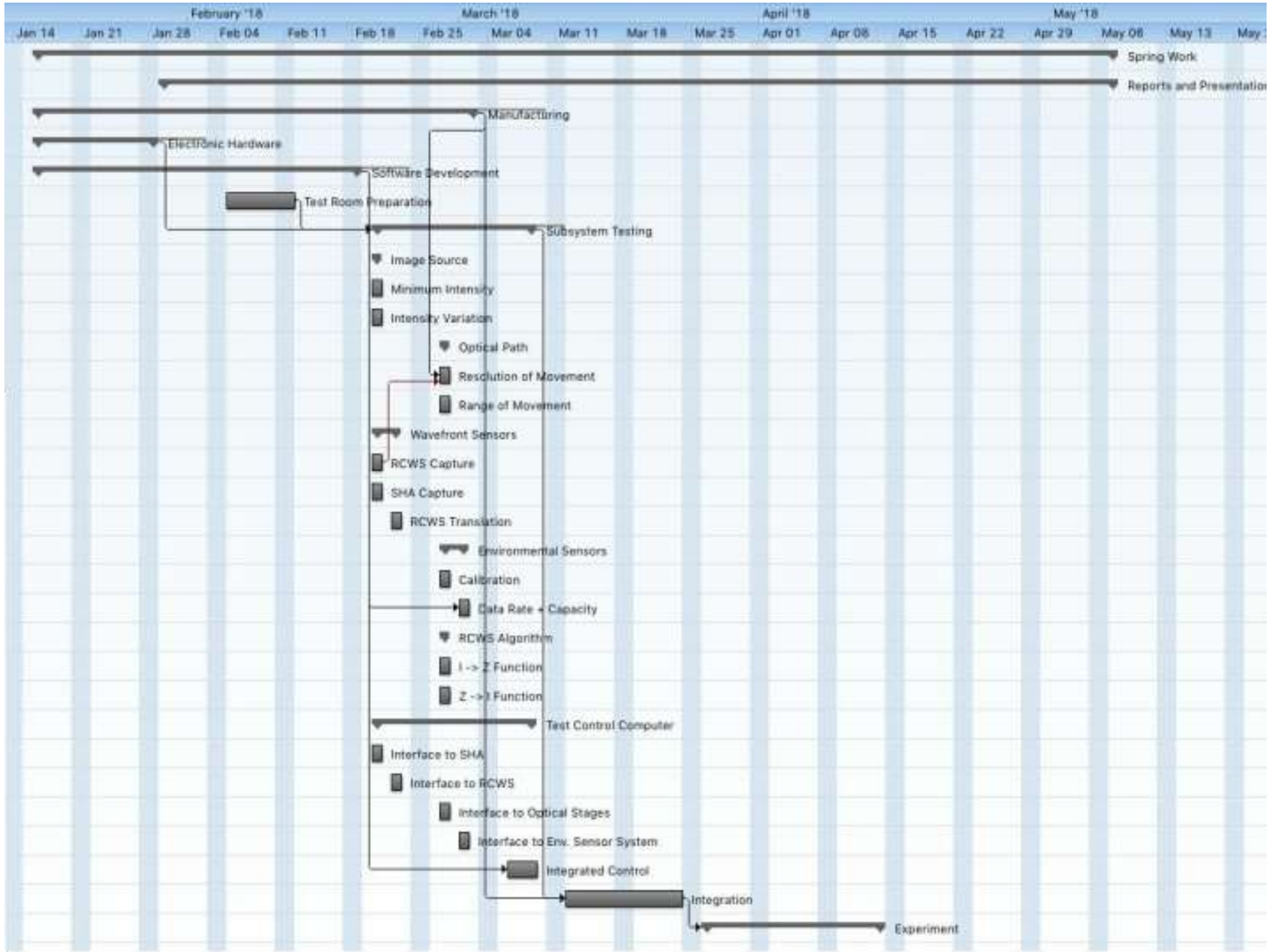
🟩 Completed as of CDR

🟥 Incomplete as of CDR

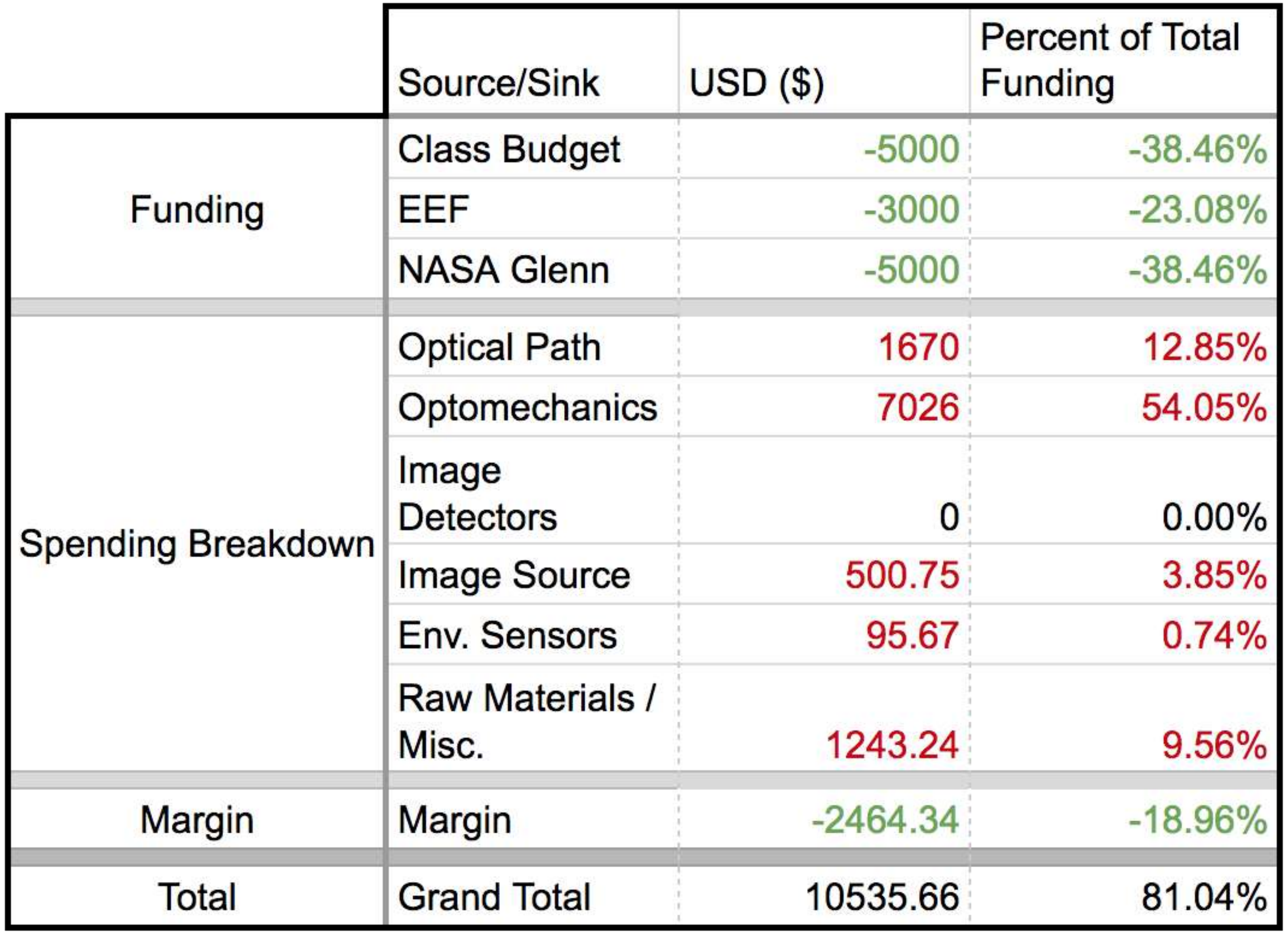
7.3 - Work Plan


February '18
March '18
April '18
May '18
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
Mar 04
Mar 11
Mar 18
Mar 25
Apr 01
Apr 08
Apr 15
Apr 22
Apr 29
May 06
May 13
May 20
Spring Work
Reports and Presentations
Manufacturing
Electronic Hardware
Software Development
Test Room Preparation
Subsystem Testing
Integration
Experiment

7.3 - Work Plan

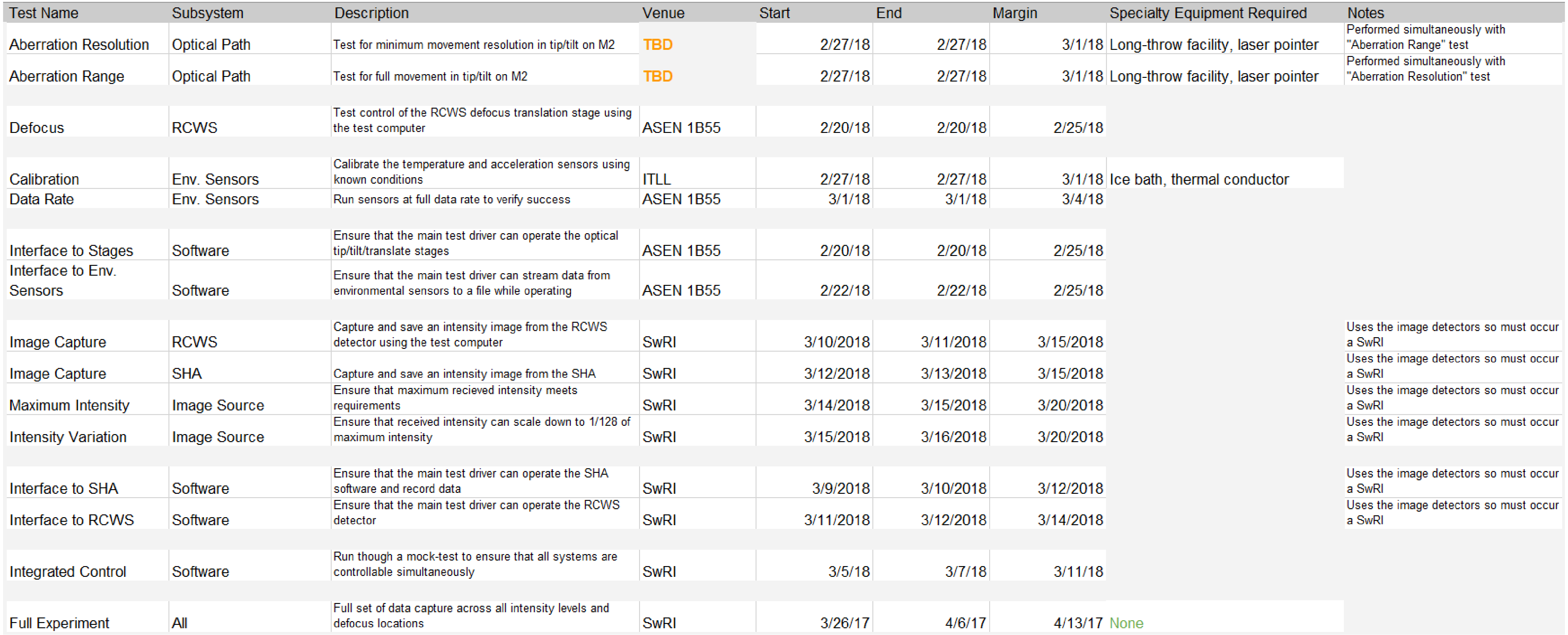

February '18
March '18
April '18
May '18
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
Mar 04
Mar 11
Mar 18
Mar 25
Apr 01
Apr 08
Apr 15
Apr 22
Apr 29
May 06
May 13
May
Spring Work
Reports and Presentatio
Manufacturing
Electronic Hardware
Software Development
Test Room Preparation
Subsystem Testing
Image Source
Minimum Intensity
Intensity Variation
Optical Path
Resolution of Movement
Range of Movement
Wavefront Sensors
RCWS Capture
SHA Capture
RCWS Translation
Environmental Sensors
Calibration
Data Rate + Capacity
RCWS Algorithm
I -> Z Function
Z -> I Function
Test Control Computer
Interface to SHA
Interface to RCWS
Interface to Optical Stages
Interface to Env. Sensor System
Integrated Control
Integration
Experiment

7.4 - Cost Plan



	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	1670	12.85%
	Optomechanics	7026	54.05%
	Image Detectors	0	0.00%
	Image Source	500.75	3.85%
	Env. Sensors	95.67	0.74%
	Raw Materials / Misc.	1243.24	9.56%
Margin	Margin	-2464.34	-18.96%
Total	Grand Total	10535.66	81.04%

7.5 - Test Plan



Test Name	Subsystem	Description	Venue	Start	End	Margin	Specialty Equipment Required	Notes
Aberration Resolution	Optical Path	Test for minimum movement resolution in tip/tilt on M2	TBD	2/27/18	2/27/18	3/1/18	Long-throw facility, laser pointer	Performed simultaneously with "Aberration Range" test
Aberration Range	Optical Path	Test for full movement in tip/tilt on M2	TBD	2/27/18	2/27/18	3/1/18	Long-throw facility, laser pointer	Performed simultaneously with "Aberration Resolution" test
Defocus	RCWS	Test control of the RCWS defocus translation stage using the test computer	ASEN 1B55	2/20/18	2/20/18	2/25/18		
Calibration	Env. Sensors	Calibrate the temperature and acceleration sensors using known conditions	ITLL	2/27/18	2/27/18	3/1/18	Ice bath, thermal conductor	
Data Rate	Env. Sensors	Run sensors at full data rate to verify success	ASEN 1B55	3/1/18	3/1/18	3/4/18		
Interface to Stages	Software	Ensure that the main test driver can operate the optical tip/tilt/translate stages	ASEN 1B55	2/20/18	2/20/18	2/25/18		
Interface to Env. Sensors	Software	Ensure that the main test driver can stream data from environmental sensors to a file while operating	ASEN 1B55	2/22/18	2/22/18	2/25/18		
Image Capture	RCWS	Capture and save an intensity image from the RCWS detector using the test computer	SwRI	3/10/2018	3/11/2018	3/15/2018		Uses the image detectors so must occur a SwRI
Image Capture	SHA	Capture and save an intensity image from the SHA	SwRI	3/12/2018	3/13/2018	3/15/2018		Uses the image detectors so must occur a SwRI
Maximum Intensity	Image Source	Ensure that maximum recieved intensity meets requirements	SwRI	3/14/2018	3/15/2018	3/20/2018		Uses the image detectors so must occur a SwRI
Intensity Variation	Image Source	Ensure that received intensity can scale down to 1/128 of maximum intensity	SwRI	3/15/2018	3/16/2018	3/20/2018		Uses the image detectors so must occur a SwRI
Interface to SHA	Software	Ensure that the main test driver can operate the SHA software and record data	SwRI	3/9/2018	3/10/2018	3/12/2018		Uses the image detectors so must occur a SwRI
Interface to RCWS	Software	Ensure that the main test driver can operate the RCWS detector	SwRI	3/11/2018	3/12/2018	3/14/2018		Uses the image detectors so must occur a SwRI
Integrated Control	Software	Run though a mock-test to ensure that all systems are controllable simultaneously	SwRI	3/5/18	3/7/18	3/11/18		
Full Experiment	All	Full set of data capture across all intensity levels and defocus locations	SwRI	3/26/17	4/6/17	4/13/17	None	

QUESTIONS?

REFERENCES

[1] RS2000 Precision Tuned Damped Research Optical Tables. Newport, 4 Dec. 2017, www.newport.com/f/tuned-damped-research-optical-tables.

[2] “ASI120MM (Mono).” ZWO ASI, ZWO Company, 29 July 2015, astronomy-imaging-camera.com/products/usb-2-0/asi120mm/.

[3] “QHY174M/C.” QHY174, QHYCCD, www.qhyccd.com/QHY174.html.

[4] “PT1-Z8 - 25 Mm (0.98’) One-Axis Motorized Translation Stage, 1/4’-20 Taps.” Thorlabs, Thorlabs, Inc., www.thorlabs.com/thorproduct.cfm?partnumber=PT1-Z8.

[5] Analog Devices, “Ultralow Power Digital MEMS Accelerometer”, http://www.analog.com/media/en/technical-documentation/data-sheets/ADXL344.pdf, ADXL344 datasheet, 2012

[6] Analog Devices, "16-Bit Digital SPI Temperature Sensor", http://www.analog.com/media/en/technical-documentation/data-sheets/ADT7320.pdf, ADT7320 datasheet, 2012

[7] “WFS150-7AR - Shack-Hartmann WFS, 150 Mm Pitch, AR Coated: 400 - 900 Nm.” Thorlabs, Thorlabs, Inc., www.thorlabs.com/thorProduct.cfm?partNumber=WFS150-7AR.

BACKUP SLIDES

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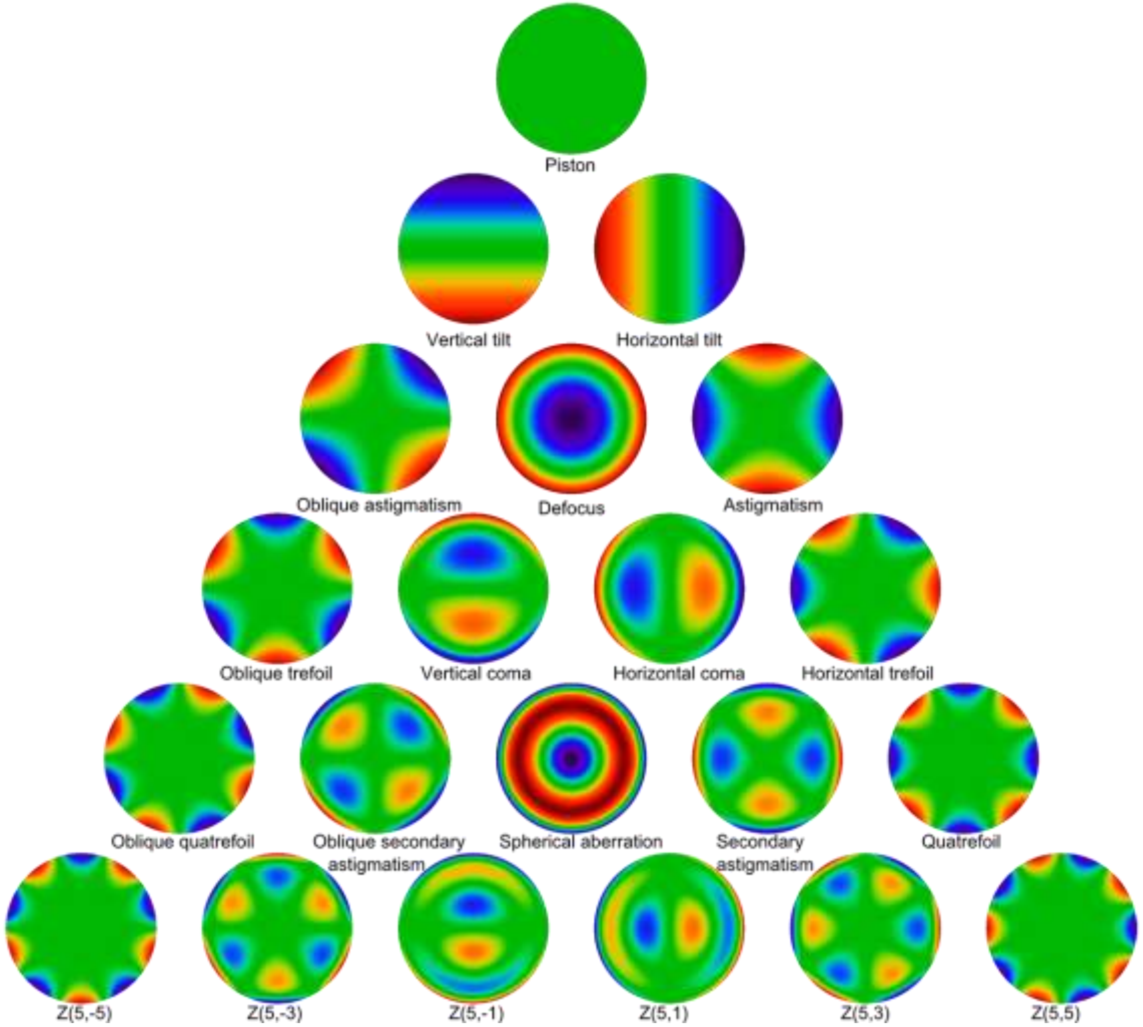
- Project Purpose and Objectives
- Design Solution
  - Image Source
  - Optical System
  - Wavefront Sensors
  - Environmental Sensors
  - Testbed
  - Test Software
- CPE/Design Requirements
  - Image
  - Optical System
  - RCWS
  - Algorithm and Software
  - Thermal/Vibration Model
  - Teensy Model
- Project Risks
- Verification and Validation
- Project Planning

Image Source

Zernike Space

- **Characteristics**:
  - A complete set of orthogonal polynomials that arise in the expansion of a wavefront function for optical systems with circular pupils.
  - Happen to have the same characteristics that images have; the use of Zernike polynomials are an approximate analytical description of the optical wavefront
  - Represented as an infinite series, but the first 11 terms are sufficient in characterizing error seen in real world systems

- **Use in this project:**
  - Describe measured wavefront error
  - Predicted in Zemax
  - Used to estimate expected images



Risk Analysis

Risk 1: Testbed not aligned correctly

- **Severity:** 5 **Likelihood:** 3 **Total:** 15
- **Description:** Testbed may not align correctly, producing unintended errors in the wavefront measurement and overall failure of our project.
- **Mitigation options:**
  - Large amount of time spent planning and 3D modeling before system is built
  - Very careful assembly of the entire system
- **Response if risk occurs:**
  - Realign the system
  - Look into alignment measurement devices

Post Mitigation Risk Analysis

- **Severity:** 5 **Likelihood:** 2 **Total:** 10

Risk Analysis

- **Risk 2: Algorithm does not correctly convert RCWS images into Zernike Polynomials**
- **Severity:** 5 **Likelihood:** 3 **Total:** 15
- **Description:** A large part of our project is developing the algorithm needed to convert the images measures on the RCWS into Zernike Polynomials; there is a risk that our algorithm may not work correctly the first time we run it. If it never runs correctly, our project will fail its main objective.
- **Mitigation options:**
  - Spend a large amount of time researching the topic before the algorithm is coded
  - Test code as it is being built during the creation of the overall algorithm
- **Response if risk occurs:**
  - Test algorithm to find which parts give results different than intended
  - Rewrite algorithm components with identified errors

Post Mitigation Risk Analysis

- **Severity:** 5 **Likelihood:** 2 **Total:** 10

Risk Analysis

- **Risk 3: Dust/fingerprints/damage introduced to optical components**

- **Severity:** 4 **Likelihood:** 4 **Total:** 16
- **Description:** Incorrect handling and storage of optical components could result in imperfections/damage to our optical hardware. Imperfect optical surfaces could result in unintended and therefore unpredicted wavefront errors being introduced into our project, which prevents us from verifying if our results are correct.
- **Mitigation options:**
  - Wearing gloves when working with all optical components
  - Storing the testbed under a dust cover
  - Being very careful when handling and assembling testbed components
- **Response if risk occurs:**
  - Attempt to clean/repair components if dirty/broken
  - If components are broken beyond repair, look into if budget allows for their replacement

Post Mitigation Risk Analysis

- **Severity:** 4 **Likelihood:** 2 **Total:** 8

Risk Analysis

- **Risk 4: Non-perfect light shroud results in leakage of light into system**
- **Severity:** 2 **Likelihood:** 3 **Total:** 6
- **Description:** If a perfect seal is not formed around our testbed, ambient light may be able to enter our system, which would introduce noise into our measurements.
- **Mitigation options:**
  - Remove every light source that feasibly can from the room
  - Spend time thinking through the design of our light shroud
  - Perform research on what others have done to shroud their testbeds from light
- **Response if risk occurs:**
  - Refine our light shroud design to make it better

Post Mitigation Risk Analysis

- **Severity:** 2 **Likelihood:** 2 **Total:** 4

Risk Analysis

- **Risk 5: Light source intensity does not remain steady**

- **Severity:** 2 **Likelihood:** 2 **Total:** 4
- **Description:** Light source intensity does not remain constant, resulting in higher signal to noise ratios and inconsistent measurements
- **Mitigation options:**
  - Perform research into components to ensure that they meet our requirements
- **Response if risk occurs:**
  - Build a signal conditioning circuit for our light source
  - Buy new components if absolutely needed and our budget allows

Post Mitigation Risk Analysis

- **Severity:** 2 **Likelihood:** 1 **Total:** 2

Risk Analysis

- **Risk 6: Non-consistent thermal and vibrational effects create inconsistent results**

- **Severity:** 3 **Likelihood:** 5 **Total:** 15
- **Description:** Inconsistent ambient temperatures and vibrations may result in thermal expansion and movement of components, producing results different from one another and different from our predictions.
- **Mitigation options:**
  - Test at “off-hours” times in order to reduce environmental vibrations
  - Test at consistent times of the day
  - Try to find the best time of day to test in
- **Response if risk occurs:**
  - Take more data and try to find correlations to the environment
  - Try to limit close human presence to testbed

Post Mitigation Risk Analysis

- **Severity:** 3 **Likelihood:** 3 **Total:** 9

Risk Analysis

- **Risk 7: Non-perfect knowledge of stage translations results in measurements different than predicted**

- **Severity:** 2 **Likelihood:** 3 **Total:** 6
- **Description:** We are trusting that our traverses will perfectly displace our optical components; therefore there is risk in a real world that they will not. This would result in different Zernike Polynomials being measured than are predicted.
- **Mitigation options:**
  - Buy translation stages with a margin of safety on tolerance that we need to align within
- **Response if risk occurs:**
  - Look into different ways in which we can measure displacement
  - Buy a new traverse if absolutely needed

Post Mitigation Risk Analysis

- **Severity:** 2 **Likelihood:** 2 **Total:** 4

Risk Analysis

- **Risk 8: Pellicle beam splitter does not perfectly split light beam**

- **Severity:** 4 **Likelihood:** 2 **Total:** 8
- **Description:** The pellicle beam splitter may not evenly distribute light, or even worse, introduce an error to one sensor and not the other, causing different unintended measurements between the two sensors when they should be the same.
- **Mitigation options:**
  - Buy a high quality beam splitter from a reputable distributor
  - Be careful when handling and placing down the beam splitter
- **Response if risk occurs:**
  - Look into aligning component better
  - Buy a new beam splitter if needed

Post Mitigation Risk Analysis

- **Severity:** 4 **Likelihood:** 1 **Total:** 4

Risk Analysis

- **Risk 9: SHA or RCWS sensors are faulty/do no work as intended**

- **Severity:** 5 **Likelihood:** 2 **Total:** 10
- **Description:** All electronic components run the risk of being manufactured incorrectly, or their datasheet may not be accurate in every single way. If they do not work, then our project cannot be carried out.
- **Mitigation options:**
  - Be careful when handling components to make sure we are not the reason they are faulty
  - Buy quality components from reputable distributors
- **Response if risk occurs:**
  - Look into obtaining new components

Post Mitigation Risk Analysis

- **Severity:** 5 **Likelihood:** 1 **Total:** 5

Risk Analysis

- **Risk 10: Imperfect manufacturing of parts causes alignment errors**
- **Severity:** 4 **Likelihood:** 3 **Total:** 12
- **Description:** If any parts are not made to the tolerances that were expected, then misalignment could occur that was not predicted in our model.
- **Mitigation options:**
  - Build a system that is able to correct for imperfections in the optical path alignment
  - Make sure that parts are manufactured with tolerances with a margin of error to meet our needs
- **Response if risk occurs:**
  - Change orientation of parts to correct for alignment errors
  - Remake parts if they are unusable

Post Mitigation Risk Analysis

- **Severity:** 4 **Likelihood:** 2 **Total:** 8

Risk Analysis

Risk 11: RCWS cannot defocus with enough resolution

- **Severity:** 4 **Likelihood:** 2 **Total:** 8
- **Description:** RCWS may need a longer translation distance or smaller steps in order to be able to measure the wavefront errors correctly.
- **Mitigation options:**
  - Build models predicting how long and how accurate of a traverse we need
  - Buy a traverse with a margin of error involved
- **Response if risk occurs:**
  - Move the traverse on the optical breadboard
  - Look into buying a new traverse if absolutely needed

Post Mitigation Risk Analysis

- **Severity:** 4 **Likelihood:** 1 **Total:** 4

Risk Analysis

- **Risk 12: Optical system model not applicable at our given Strehl Ratio of 0.7**
- **Severity:** 3 **Likelihood:** 2 **Total:** 6
- **Description:** Our models all assume a Strehl Ratio of 1.0; however, in our real system, 0.7 is more likely to be achieved. This may result in models predicting numbers very slightly different from what is predicted.
- **Mitigation options:**
  - Careful handling of equipment
  - Carefully execute a well thought out alignment procedure
- **Response if risk occurs:**
  - Try to increase the Strehl Ratio if it is too low by realigning the system

Post Mitigation Risk Analysis

- **Severity:** 3 **Likelihood:** 1 **Total:** 3

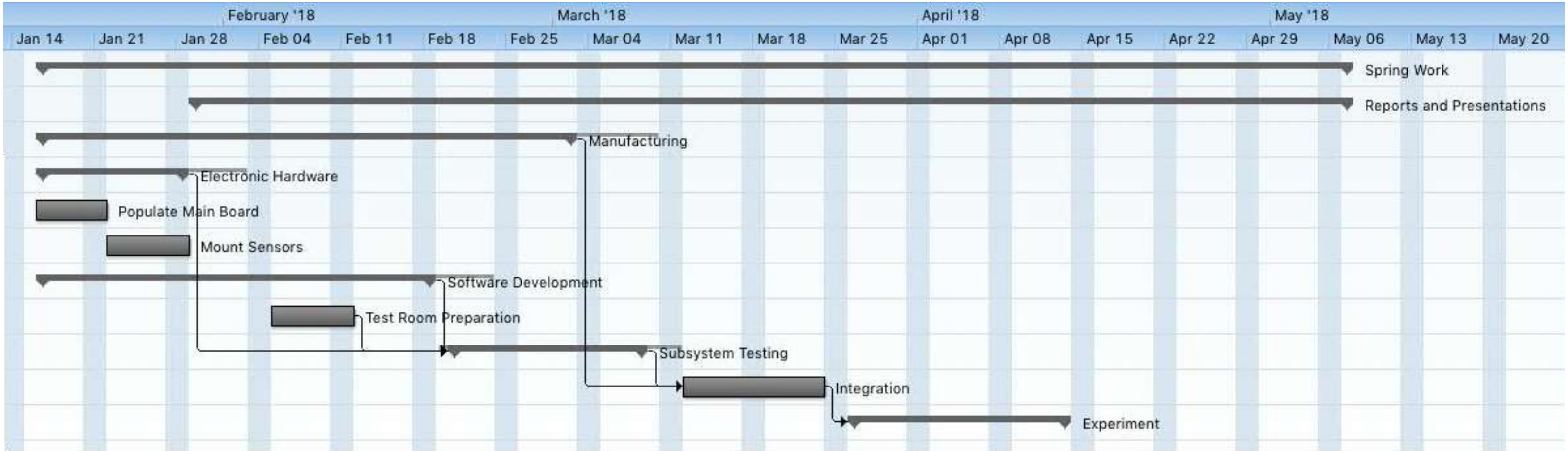
Risk Analysis

- **Risk 13: Entire test procedure may not be able to be fully automated, introducing the risk for human error in all unautomated processes**
- **Severity:** 3 **Likelihood:** 3 **Total:** 9
- **Description:** An API is being developed to fully automate the entire data collection process; however, if it is not possible to write this, then the process will have to be manually stepped through. Doing so could result in steps being skipped/not implemented in the right order, resulting in incorrect data being recorded.
- **Mitigation options:**
  - Schedule ample time in order to develop an automated system
  - Look into reducing process complexity wherever possible
- **Response if risk occurs:**
  - Look into getting advice from someone with a lot of expertise
  - Write a checklist and strictly follow it if procedure has to be done manually

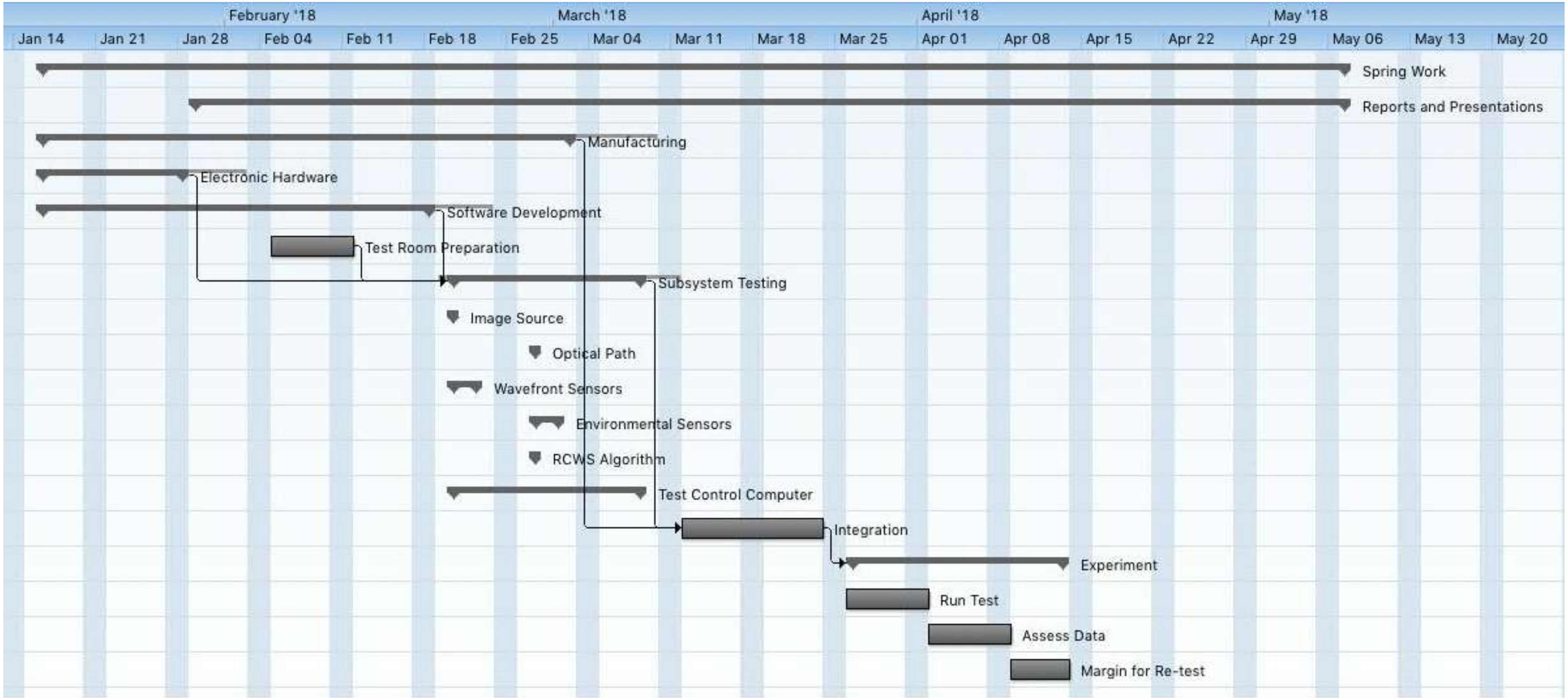
Post Mitigation Risk Analysis

- **Severity:** 3 **Likelihood:** 2 **Total:** 6

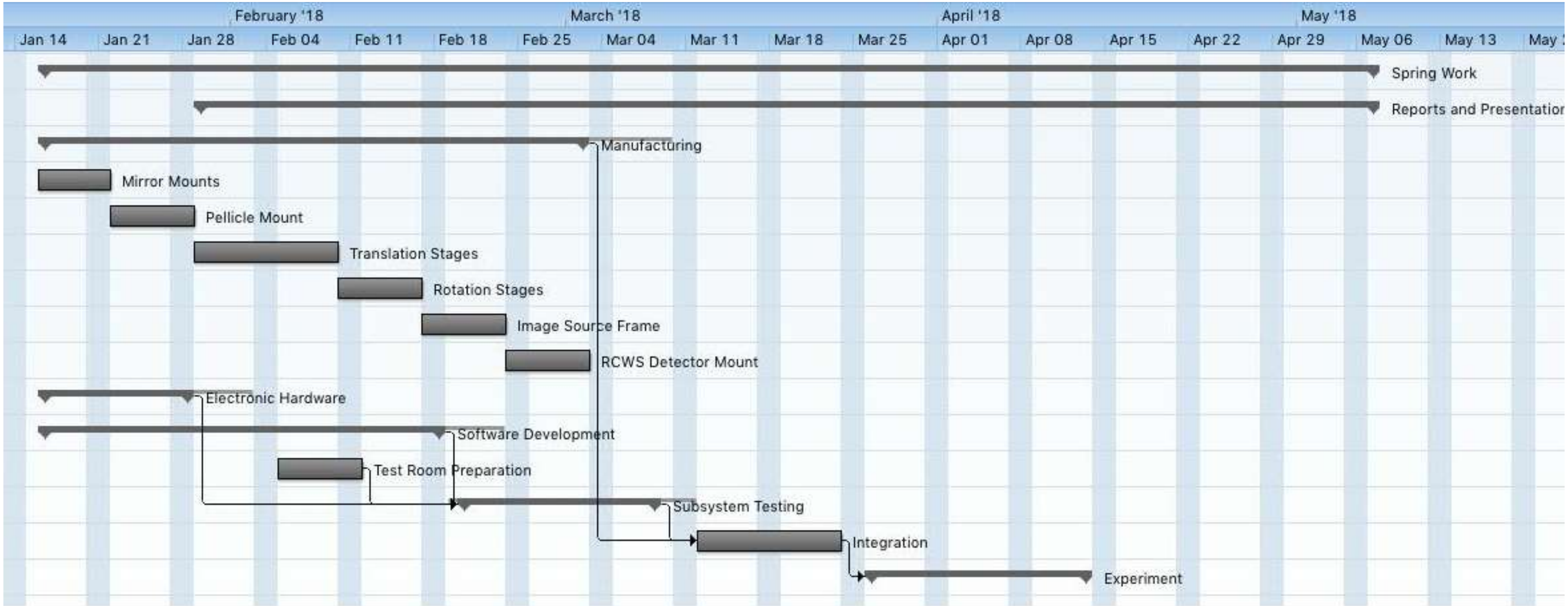
Detailed Work Plan



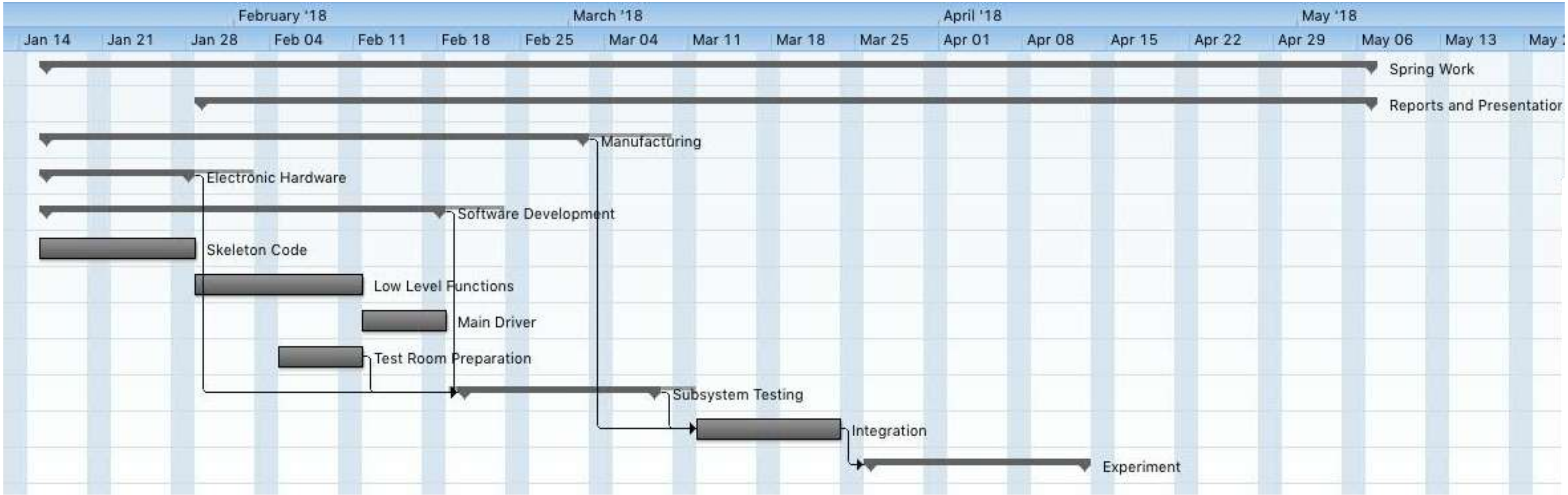
Detailed Work Plan



Detailed Work Plan



Detailed Work Plan



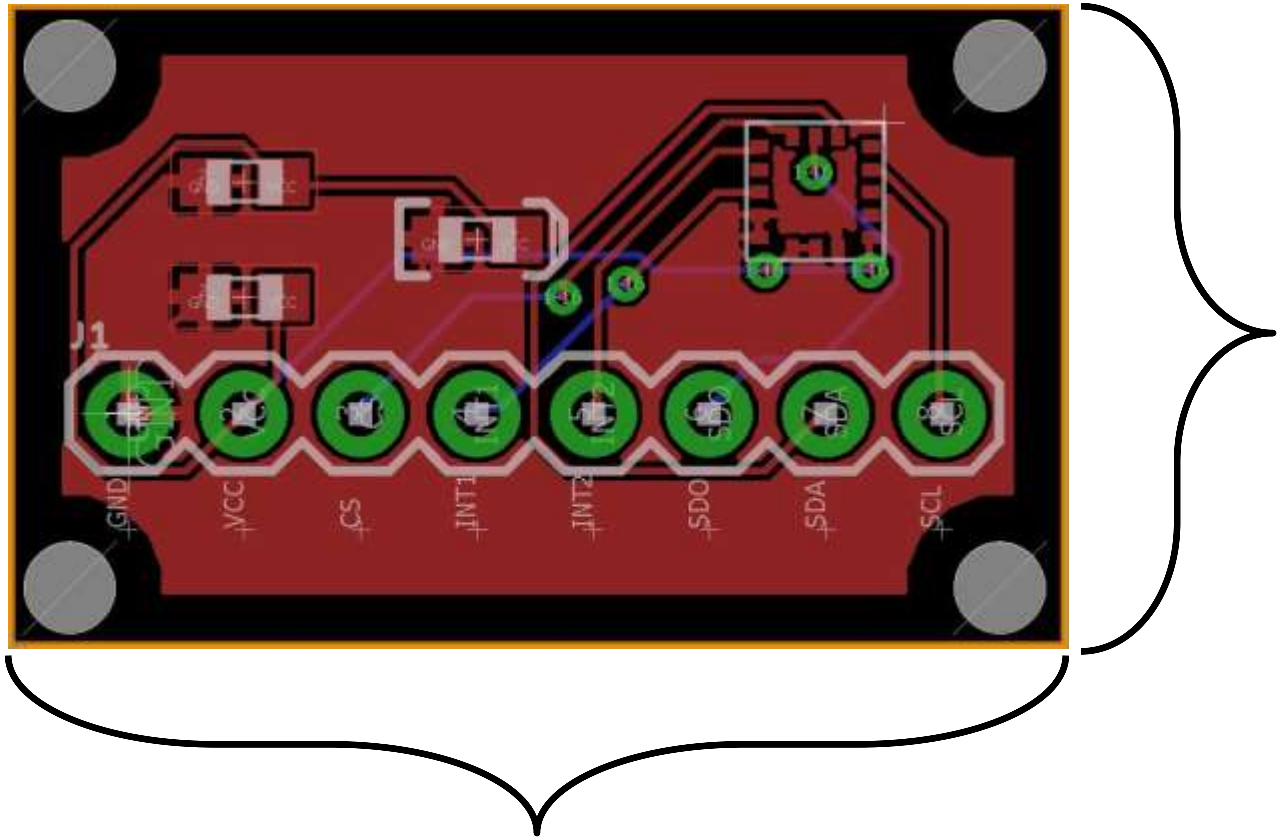
Detailed Cost

AWESoMe Bill of Materials

https://docs.google.com/spreadsheets/d/1Dohc0TzLgpM99-pKKX4CHPMiPW7tQCktbKuPYSjQO9E/edit#gid=0

Environmental Sensors – Board / Sensor Layouts

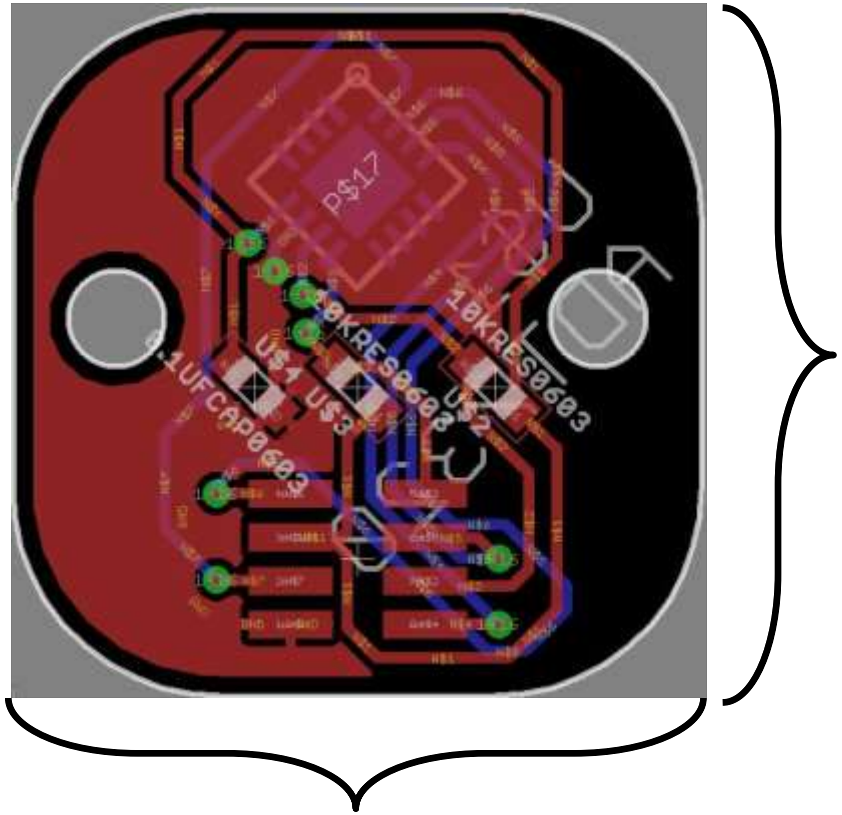
ADXL344 Breakout:



$14mm$

$23mm$

ADT7320 Breakout:

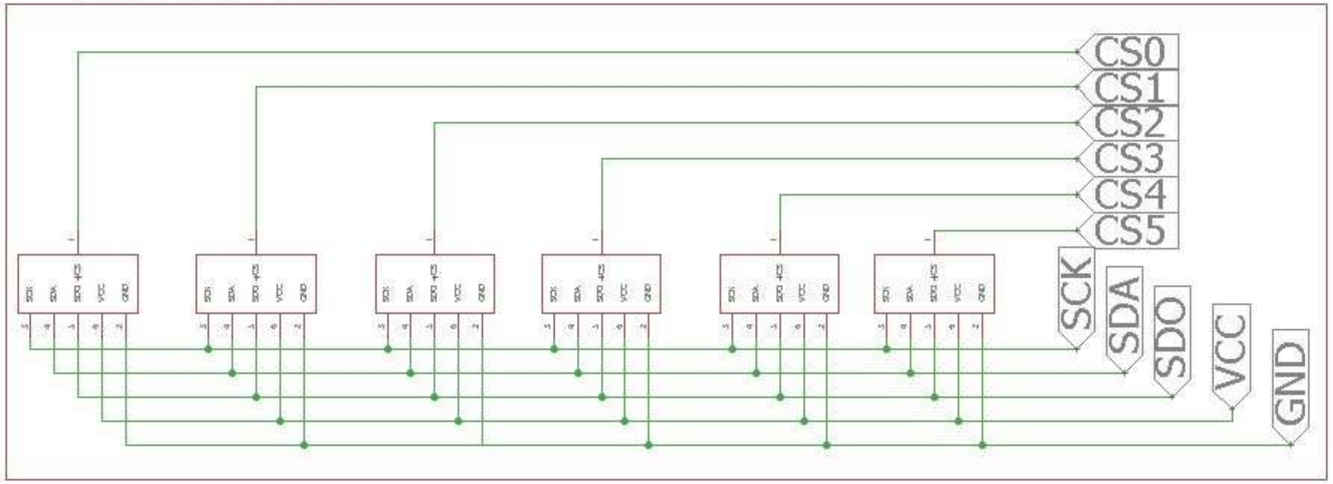


$20mm$

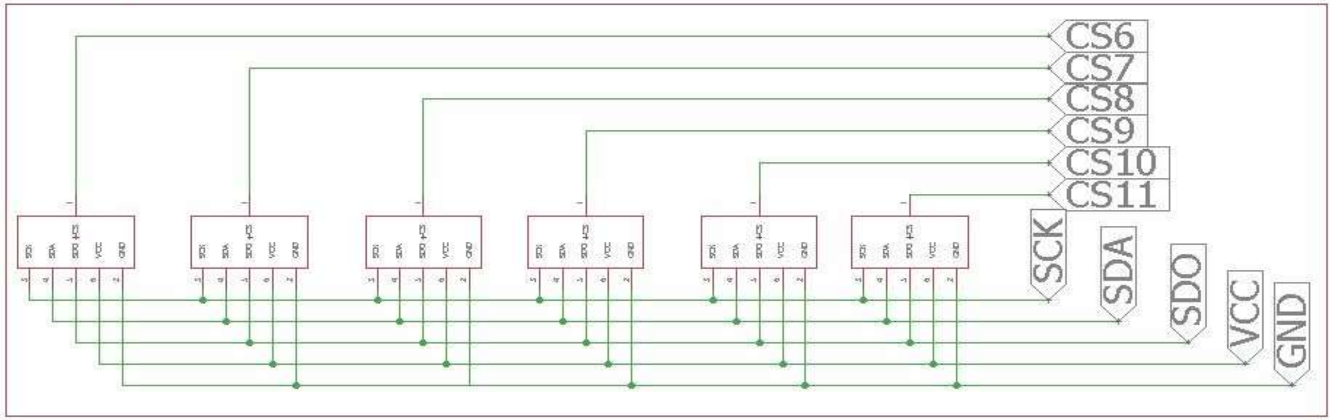
$20mm$

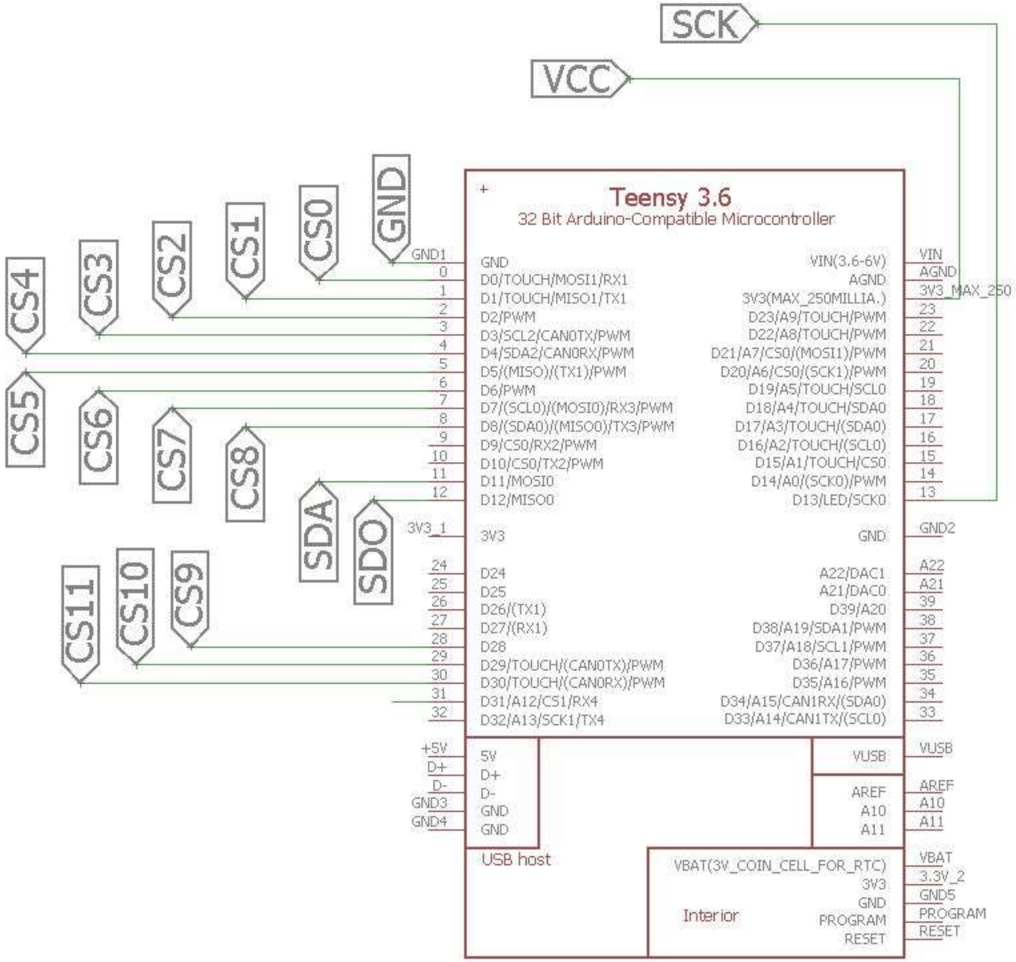
Environmental Sensors – Teensy Layout

Accelerometers



Temperature Sensors





Appendix: Transport of Intensities Equation

$$\frac{\partial I}{\partial z} = \frac{\lambda F\,(F-l)}{2\pi l}\left[\frac{\partial}{\partial n}\phi\left(\frac{F\vec{r}}{l}\right)\delta_c - \nabla^2\phi\left(\frac{F\vec{r}}{l}\right)\right]$$

$\frac{\partial I}{\partial z}$ is the rate of change of the intesity along the optical axis (approximately the difference in intensity in the two images).

F is the focal length, λ is the wavelength, and l is the distance between where the two images are taken.

$\frac{\partial}{\partial n}\phi\left(\frac{F\vec{r}}{l}\right)\delta_c$ is the slope of the wavefront, along the edge of the beam

$\nabla^2\phi\left(\frac{F\vec{r}}{l}\right)$ is the laplacian of the waveform (the amount of curvature)

Transport of Intensities Equation (TIE)

- Difficult part of solving the TIE is computing the inverse Laplacian (going from information about curvature of the wavefront to the surface itself)
- In practice, transform to a domain where the Laplacian operator is simpler
  - Fourier domain
  - Zernike domain
- Then the inverse Laplacian can be computed using IFFT/Matrix inversion

Roddier Curvature Wavefront Sensor Feasibility

- To determine how feasible the minimum displacement is, one must determine how accurately we can define the true location of the RCWS as it is being physically translated.

Potential linear stage Characteristics:

- Total Displacement: 25mm
- Min. achievable Incremental Movement: $0.05[\mu m]$.
- Bidirectional Uncertainty: $< 1.5[\mu m]$.

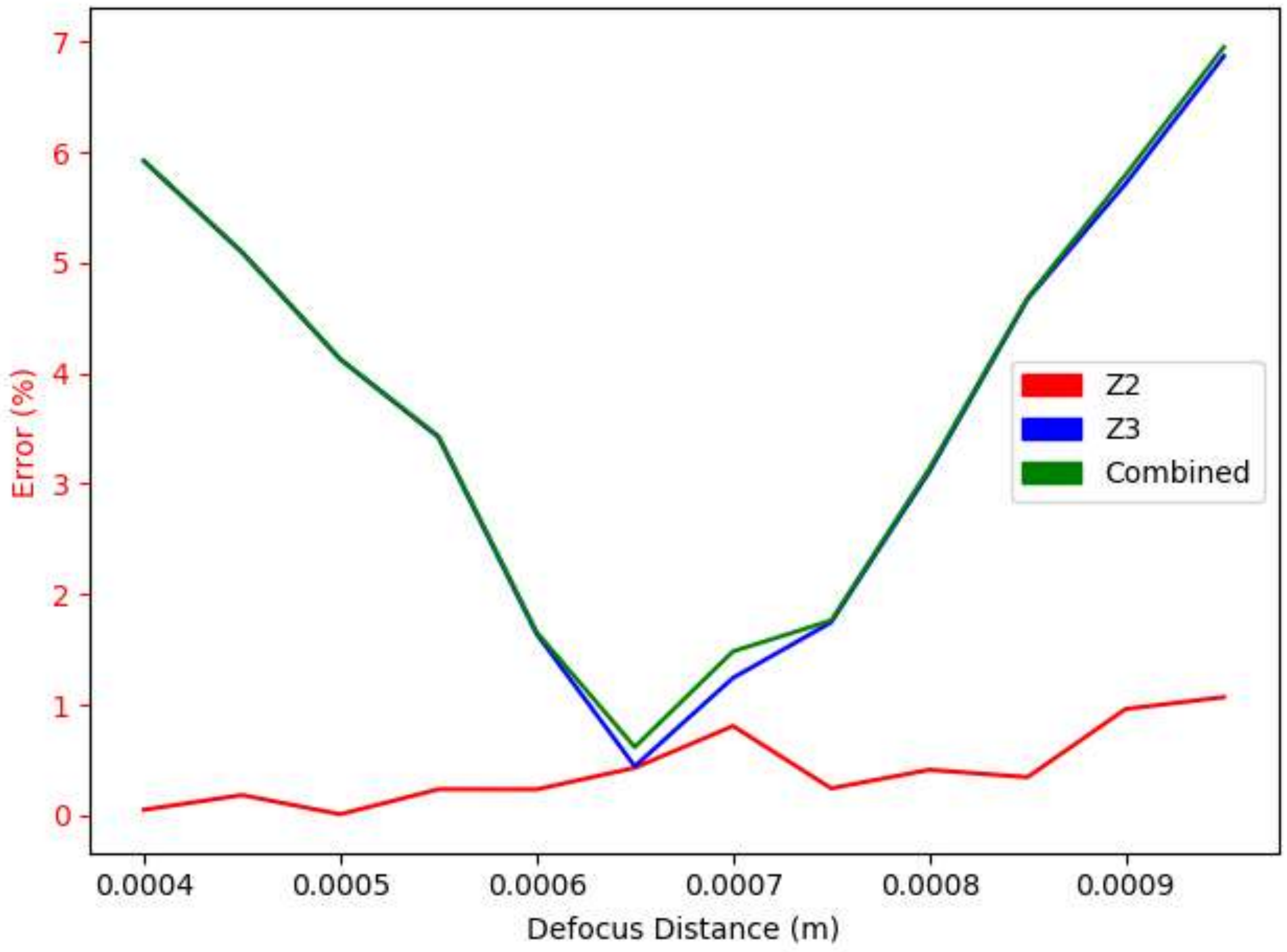
- Comparing the minimum displacement of the RCWS to the bidirectional uncertainty of the linear stage yields the fractional uncertainty:

$$Uncertainty = \frac{Bidirectional\ Uncertainty}{minimum\ RCWS\ displacement}$$

$$Uncertainty = \frac{1.5[\mu m]}{204.13[\mu m]} \times 100$$

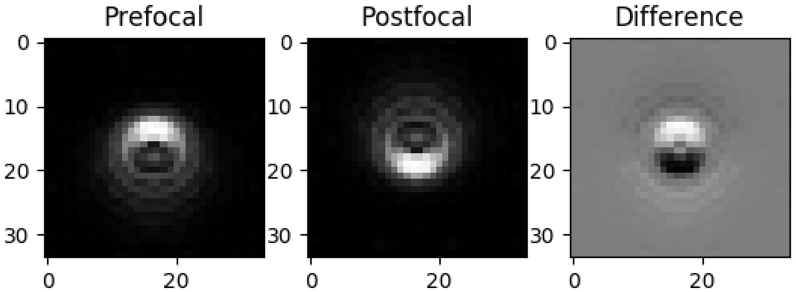
$$Uncertainty = 0.735\%$$

Synthetic Model Error in Tip and Tilt

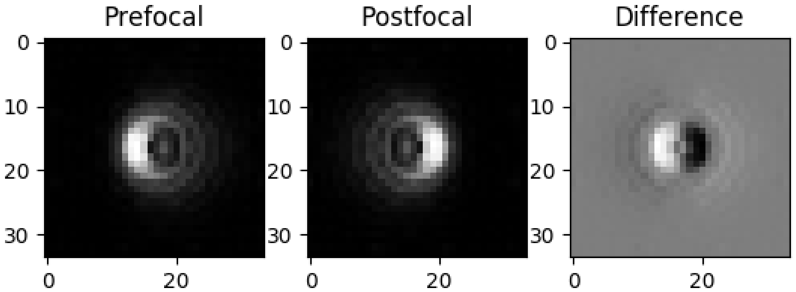


- Using a numerical method to solve for the percent error in Tip (Z2) and Tilt (Z3).
- The optimal defocus distance for the RCWS would minimize the percent error.
- When Z4-Z11 are included for the model, the minimal error defocus distance will be expected to shift slightly larger, as higher order Zernikes require more intensity values to resolve.

Zernike Aberration Differences (±720µm Defocus)

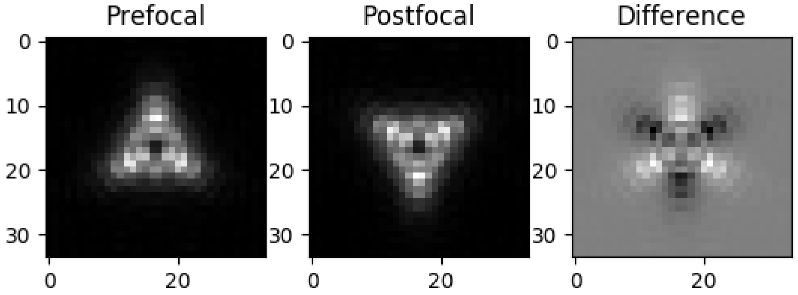


Z7: Y Coma

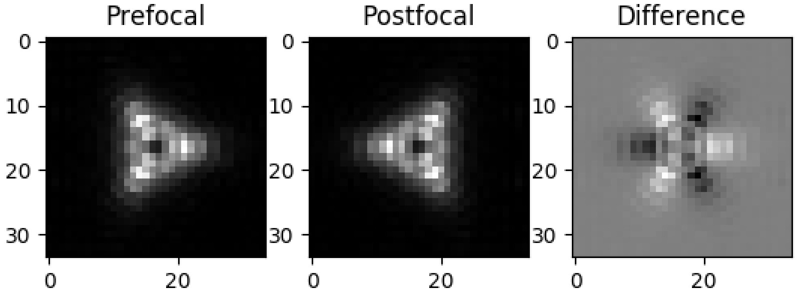


Z8: X Coma

Zernike Aberration Differences (±720μm Defocus)

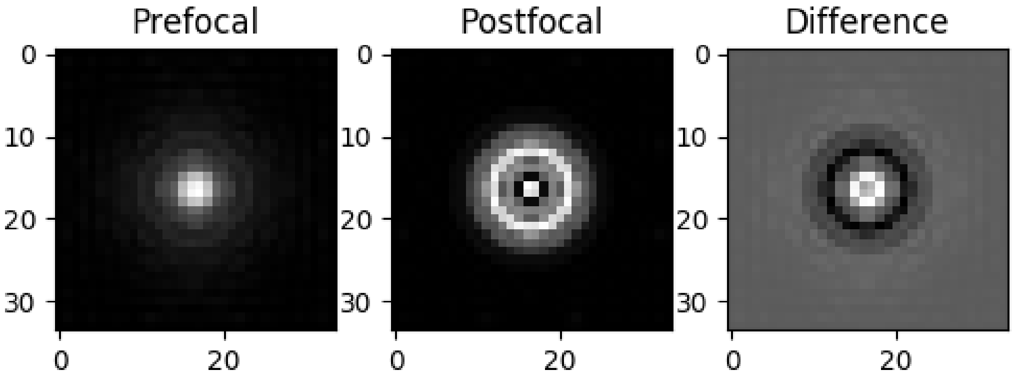


Z9: Y Trefoil



Z10: X Trefoil

Zernike Aberration Differences (±720µm Defocus)



Z11: Spherical