Apparatus for Wavefront Error Sensor Measurement:
Test Readiness Review

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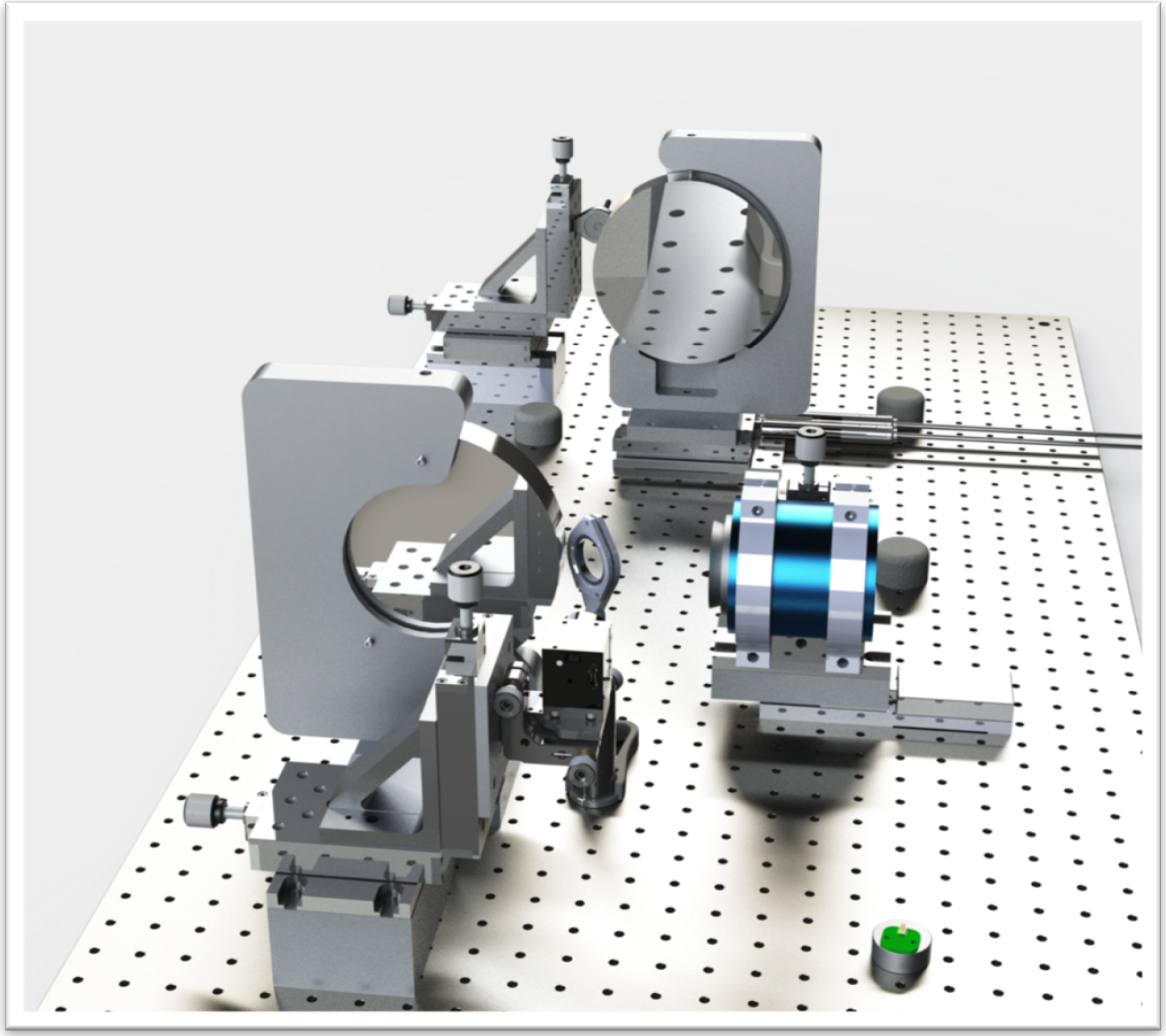


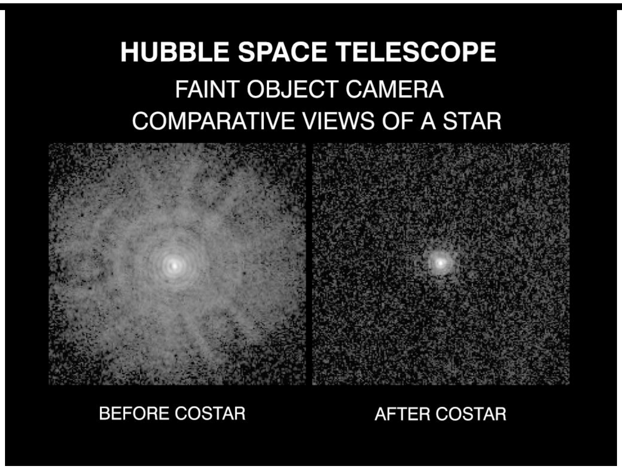
1.1 – Background
1.2 – Project Success
1.3 – Critical Elements for Testing
1.4 – CONOPS
1.5 – FBD

1.0 – OVERVIEW

1.1 – Background

Wavefront Sensing:

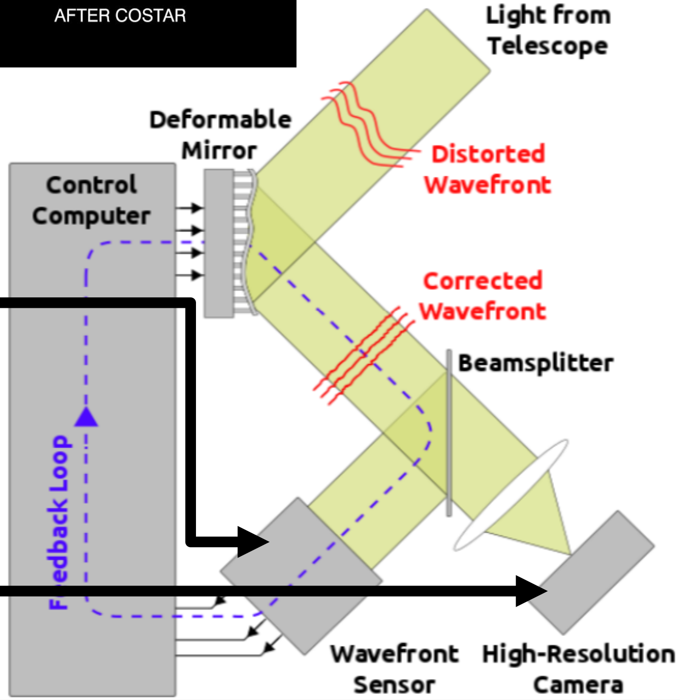
- A wavefront is a constant-phase surface of light emanating from a single source
- Wavefront error is non-uniform and induces distorted images



Corrective Optics Space Telescope Axial Replacement (COSTAR)

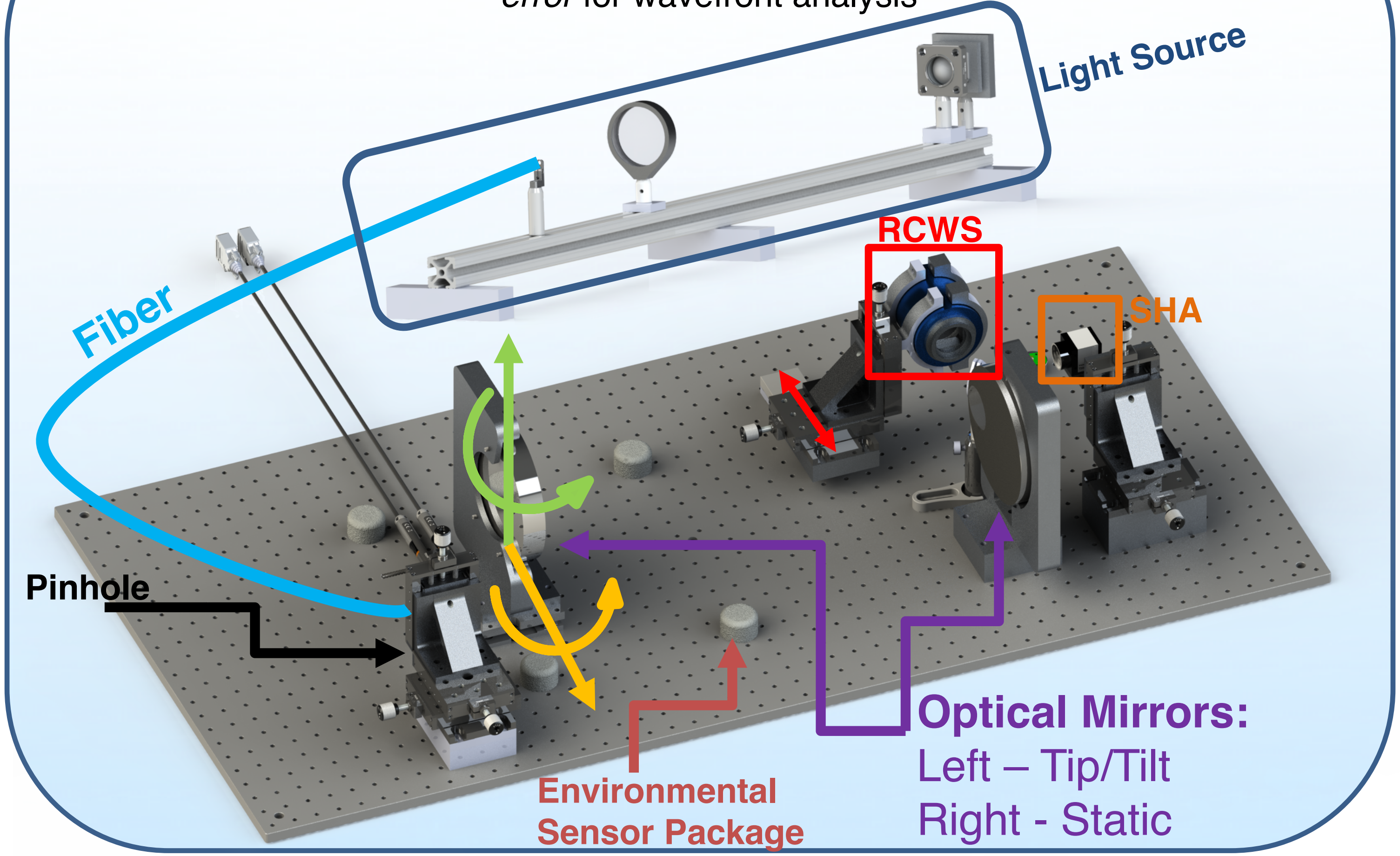
Wavefront Sensors (WFS):

- 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



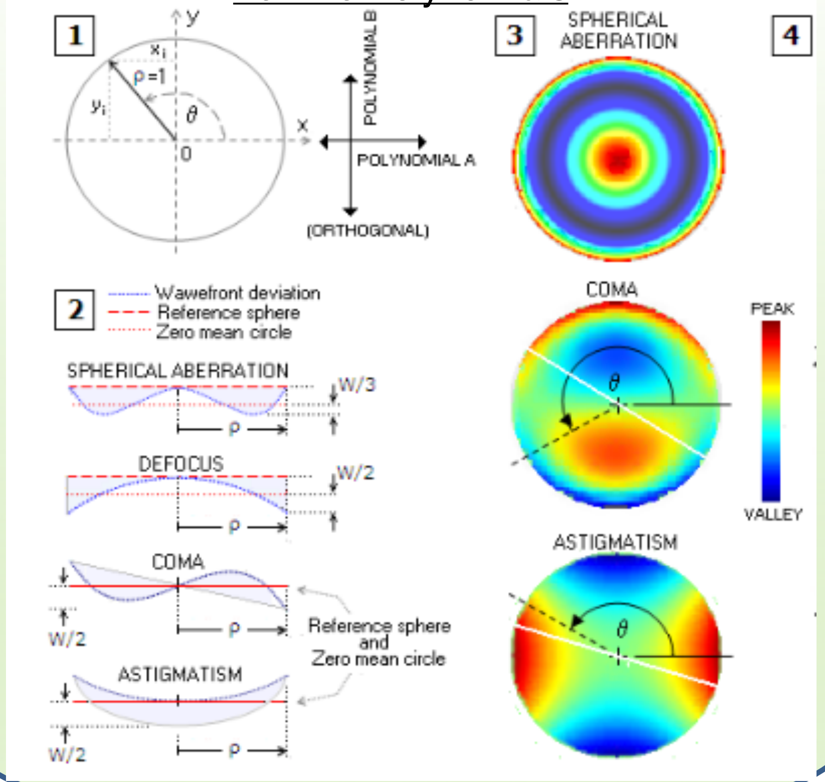
1.2 – Project Success

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



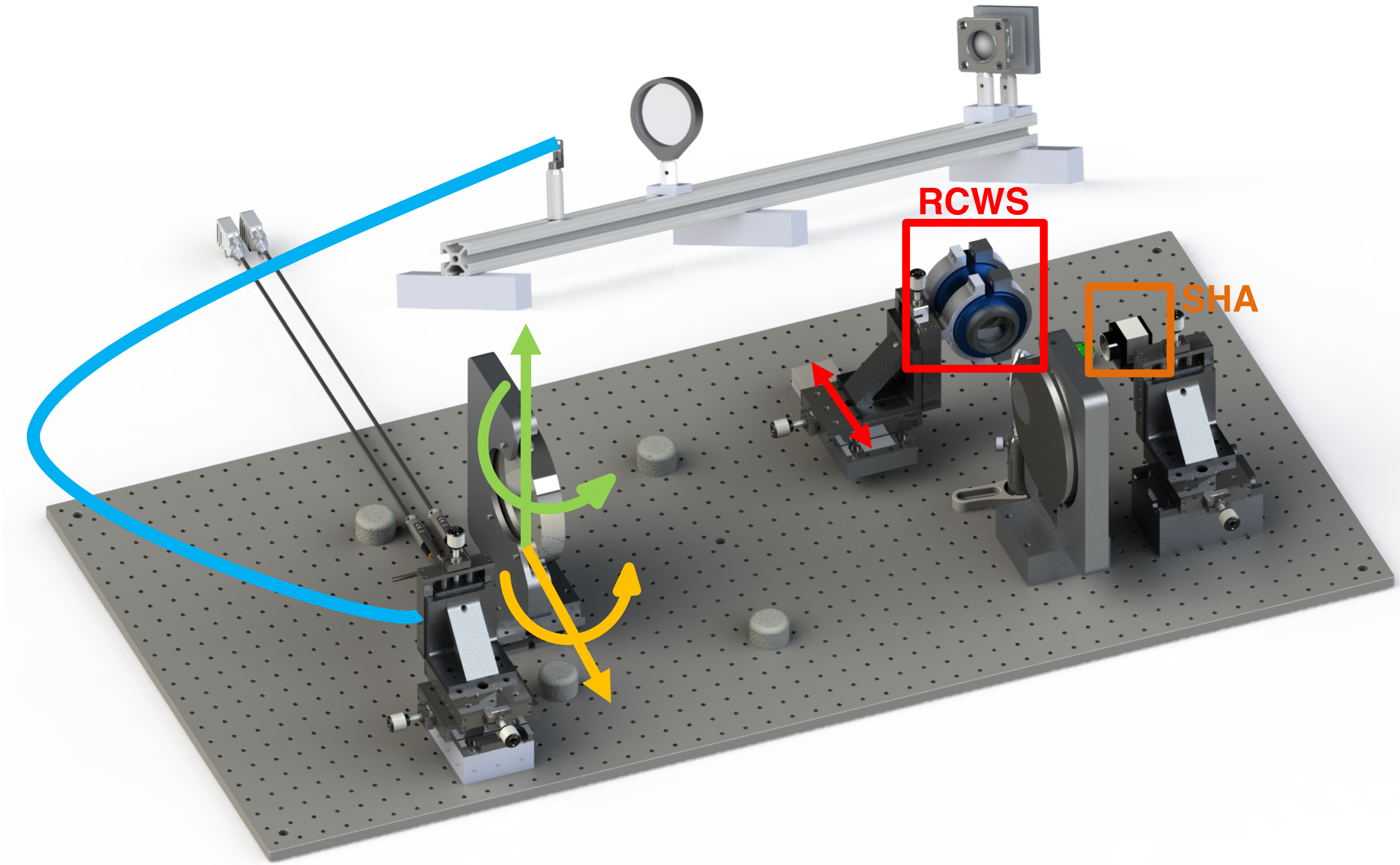
Level 2: Implement RCWS algorithm from Level 1 data and compare to SHA results expressed in the *rate of change of Zernike Polynomials* with respect to mirror movement

<u>Zernike Polynomials</u>



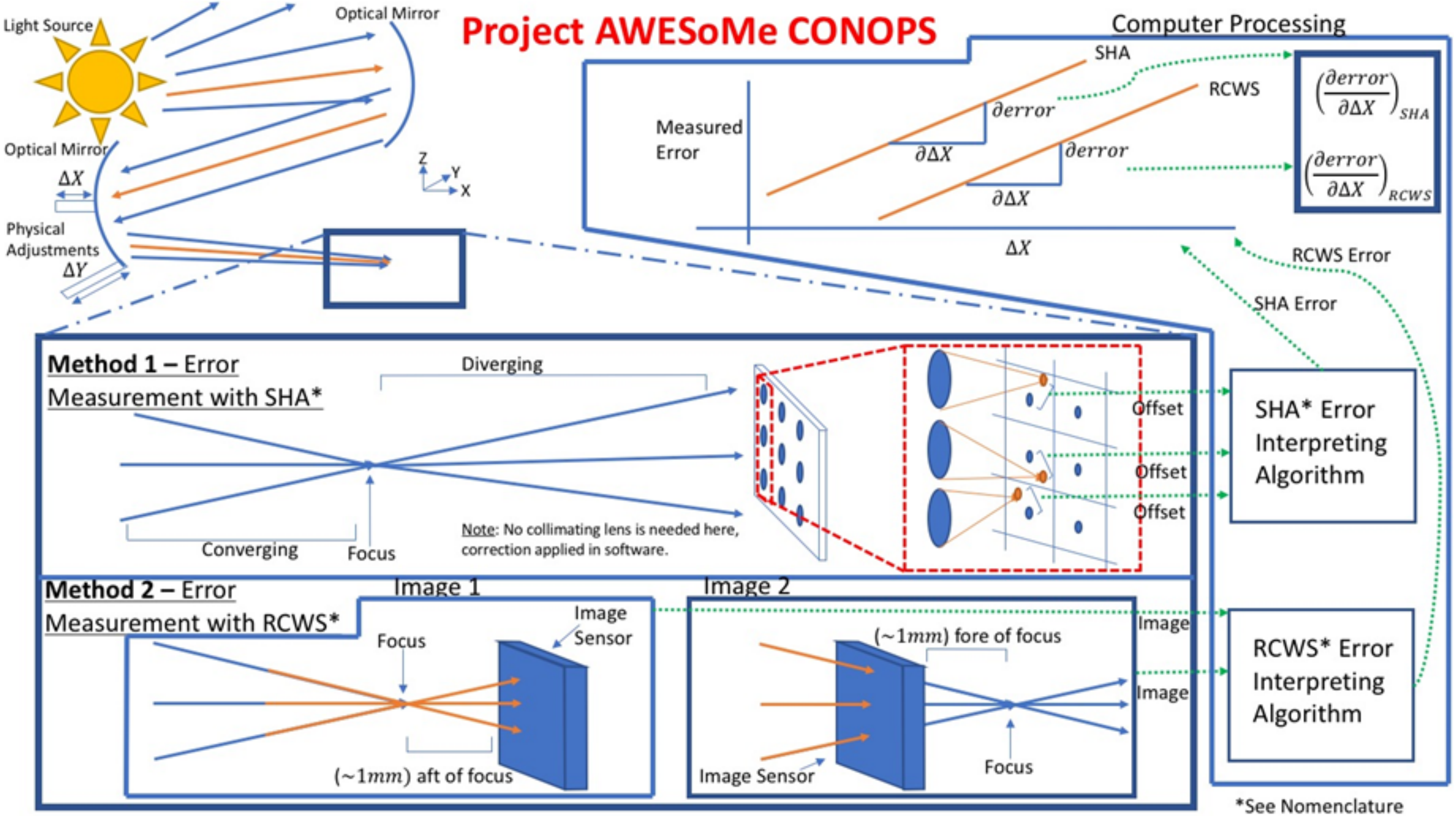
1.3 – Critical Elements for Testing

Level 1 Success

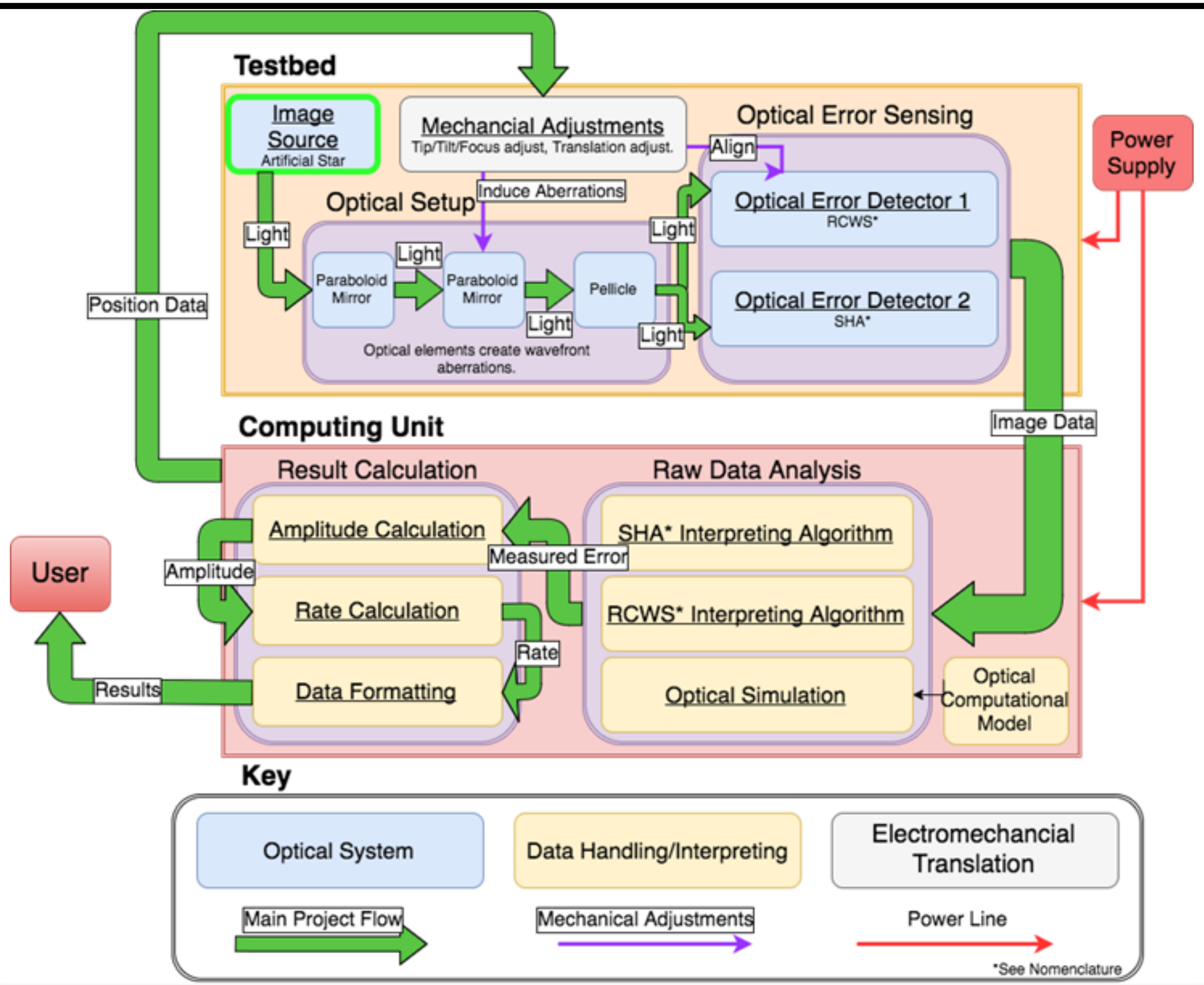


1. **Received Energy Modulation**
   - Compare sensors for low-light conditions
2. **Mirror Tilting Resolution**
   - Confirm tip/tilt stage is capable of moving more resolved than required
3. **Linear Traverse Resolution**
   - Confirm linear stage is capable of moving more resolved than required
4. **Data Collection and Hardware Automation**
   - Confirm whole setup is operating as expected

1.4 – Concept of Operations



1.5 – Functional Block Diagram



2.1 – SNR and Received Energy Variation
2.2 – Wavefront Manipulation
2.3 – RCWS Movement
2.4 – Data Collection

2.0 – TEST READINESS

2.1 – SNR & Received Energy Variation

Varying received intensity for comparison between SHA and RCWS to compare low-light performance between sensors.

ID	Requirement
3.1	A 100 SNR for image sensors at maximum exposure time.
3.2	Energy received by sensors must then be reduced by increments of half until 1/128th of maximum.

<u>To be verified experimentally in three parts:</u>

- Characterize noise terms for model
- Verify model of maximum exposure time
- Verify received energy model over range of exposure times

$$\underbrace{\boxed{Counts}}_{\text{Measured signal}} = \underbrace{\boxed{srcCounts}}_{\text{Expected signal}} + \underbrace{\boxed{\sigma_{src} + \sigma_{dcr} + \sigma_{BG} + RN}}_{\text{Noise terms}}$$

$$SNR = \frac{srcCounts}{\sqrt{\sigma_{src}^2 + \sigma_{dcr}^2 + \sigma_{BG}^2 + RN^2}}$$

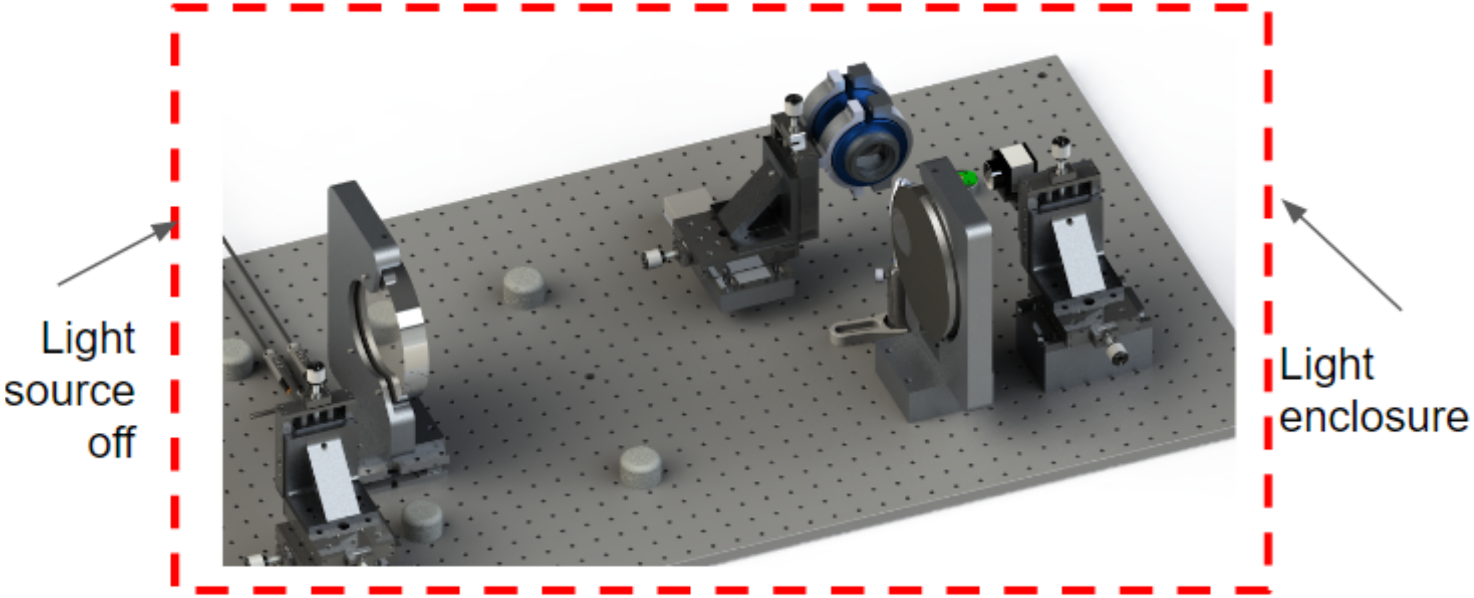
$$srcCount = (G \cdot Q \cdot A \cdot f) \cdot \Delta t, \ \ \sigma_{src} \approx \sqrt{srcCounts}$$

2.1.1 – Sensor Noise

What:	Characterize "zero-light" noise in the image sensors.
How:	Read image sensor data with: •Image source turned off •System enclosed in light-blocking enclosure.
Why:	Experimentally defines the sensor noise terms for verifying maximum exposure time needed and finding *srcCounts* in subsequent tests.

$$Counts = \underbrace{srcCounts}_{0} + \underbrace{\sigma_{src}}_{0} + \sigma_{dcr} + \sigma_{BG} + RN$$

$$Counts = \sigma_{dcr} + \sigma_{BG} + RN$$



2.1.2 – Maximum Exposure Time

What:	• Calculate the exposure time to yield 100 SNR. • Verify that calculated first order approximated exposure time to yield 100 SNR.
Why:	• Validate satisfaction of Req 3.1. • Maximum exposure time is the basis of exposure times expected from Req 3.2.
How:	Read image sensor data (at the approximated exposure time): • Use this Counts reading to experimentally verify the SNR.

G: Gain
Q: Quantum Efficiency
A: Capture Area
f: Photon Flux

$$srcCounts = (G \cdot Q \cdot A \cdot f) \cdot \Delta t$$

Solving for exposure time

$$\Delta t = \frac{srcCounts}{G \cdot Q \cdot A \cdot f}$$

At high SNR, *srcCounts* is expected to dominate and can be approximated as such:

$$100 \approx \sqrt{srcCounts}$$

2.1.3 – Received Energy Variation

What:	• Verify that changing exposure time changes energy received by sensors as calculated in model • Verify that source's light output does not vary with time
Why:	• Validates that we satisfy REQ 3.2 • Project relies on accurate intensity control to characterize cameras at different brightness to see where performance degrades

How:	• Compare CMOS outputs to model at calculated exposure times
	    • Ensures that incoming light is varied as expected
	• Check time-variance of source output
	    High frequency 1/7680s exposures over 1/60s
	    Low frequency 1/60s exposures over 10s

$$Counts = \overbrace{srcCounts + \sigma_{src}}^{\text{Proportional}} + \overbrace{\sigma_{dcr} + \sigma_{BG} + RN}^{\text{Determined previously}}$$

Recall:

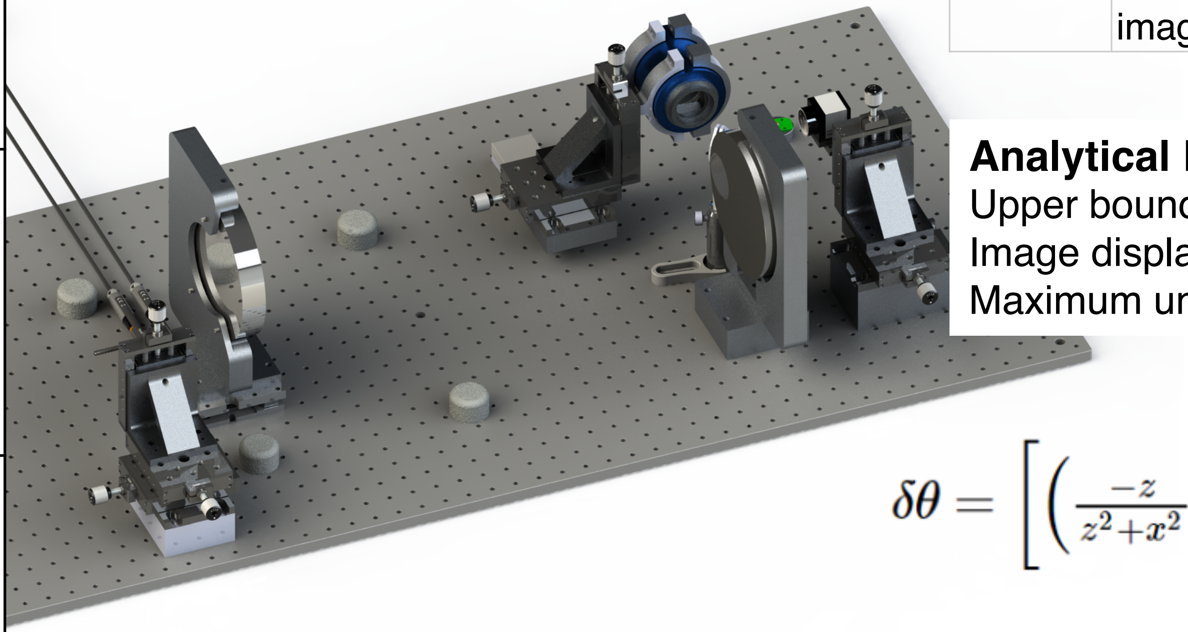
Held constant by image source

$$srcCounts = (\overbrace{G \cdot Q \cdot A}^{\text{Characteristic of camera}} \cdot f) \cdot \Delta t$$

$$\Longrightarrow \quad srcCounts \propto \Delta t$$

2.2 – Wavefront Manipulation

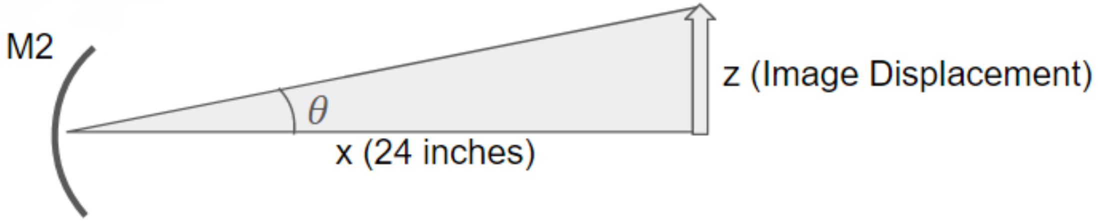
What:	Validate that tip/tilt resolution allows for introduction of wavefront error with a resolution of λ/15 which corresponds to a tip of ~266 arcsec
Why:	Reality check that the tip/tilt platform performs better than the required resolution for wavefront introduction to be observed by the SHA
How:	Relate angular resolution on tip/tilt stage to introduction of RMS wavefront error, measure tip/tilt resolution



ID	Requirement
2.2.1	Wavefront error shall be introduced in resolution equal to or exceeding a RMS optical path delay of λ/15, where λ is the center wavelength of the image source

Analytical Results:
Upper bound: $\delta x = 0.0254$ *m*
Image displacement resolution: $\delta z = 9.375 \times 10^{-7}$ *m*
Maximum uncertainty in Tip: $\delta\theta = 0.4346$ *arcsec*

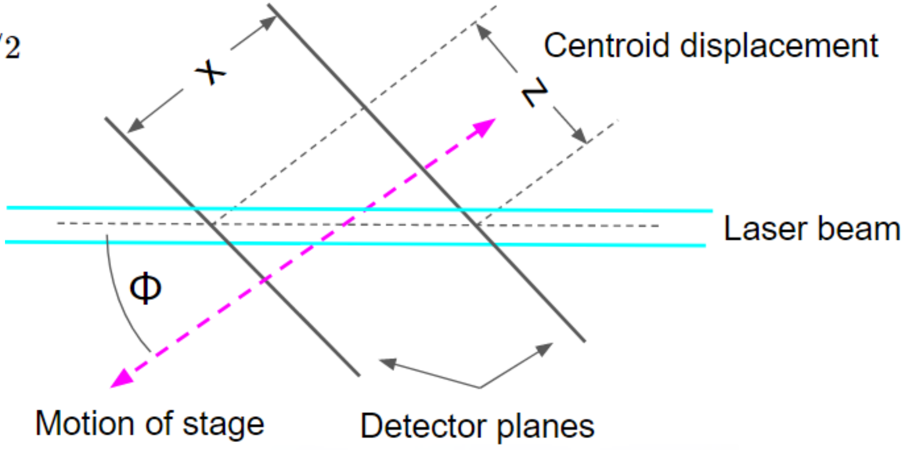
$$\delta\theta = \left[\left(\frac{-z}{z^2+x^2}\right)^2(\delta x)^2 + \left(\frac{x}{z^2+x^2}\right)^2(\delta z)^2\right]^{1/2}$$



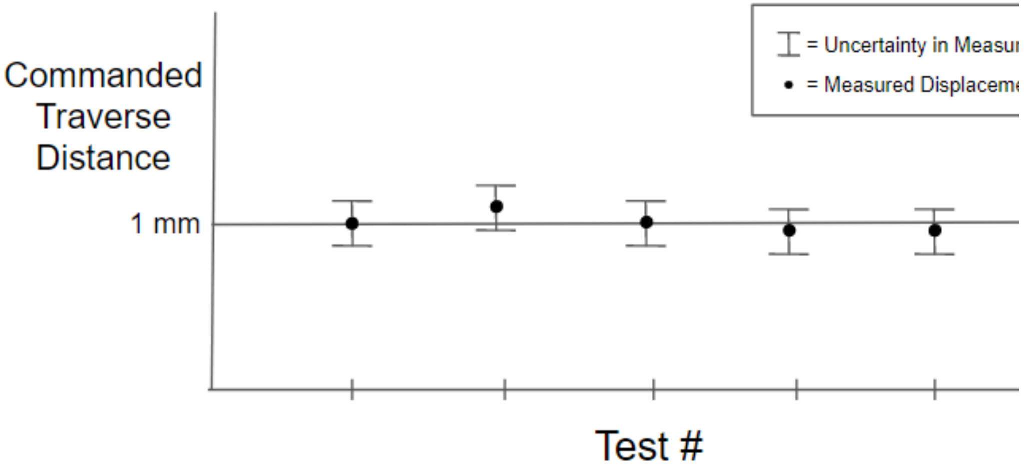
2.3 – RCWS Movement

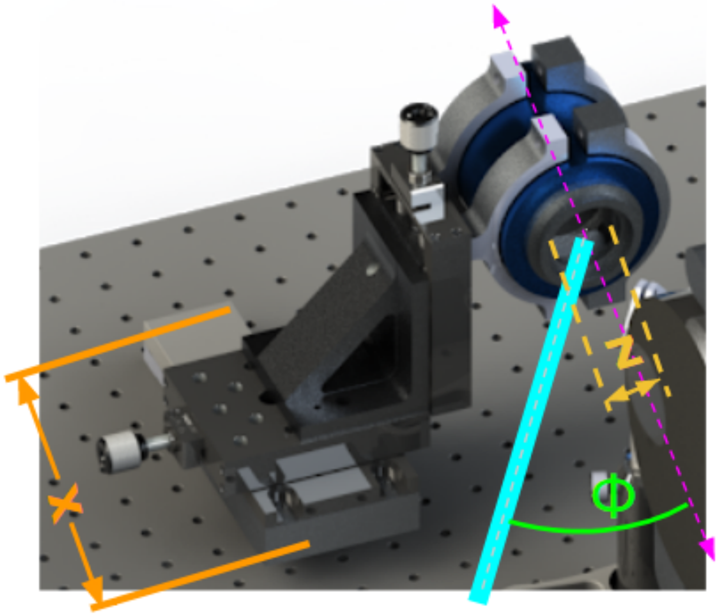
What:	Find maximum uncertainty in this measurement to propagate through our equations
Why:	The Transport of Intensities Equation (TIE) depends on RCWS displacement distance x
How:	• Set RCWS at angle Φ (45°) from laser beam • Command the RCWS to move a distance of x = 1 mm • Find z by finding displacement of image centroid on sensor

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



Analytical Results:
With Φ uncertainty of 2°, and pixel size of 3.75 µm leading to an uncertainty in z of 9.375 × 10-7 m, we end up with a total uncertainty of 6.982% in the RCWS displacement distance x

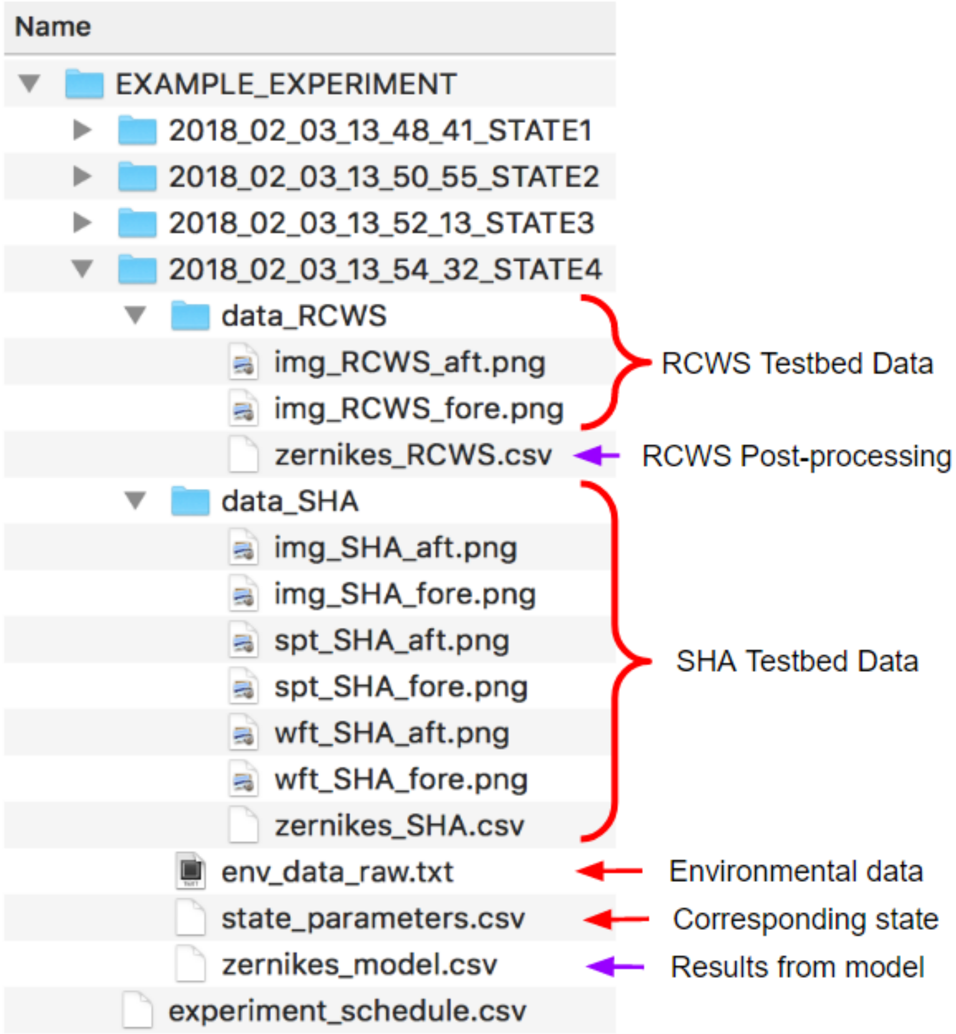




2.4 – Data Collection

- In order to prove that the system works as a whole it will be used to collect one set of experimental data that could be analyzed later

- Reduces risk to the project by actually collecting data while the system is aligned. (After we move out of the lab, alignment will have to be performed again to take more data)



experiment_schedule.csv

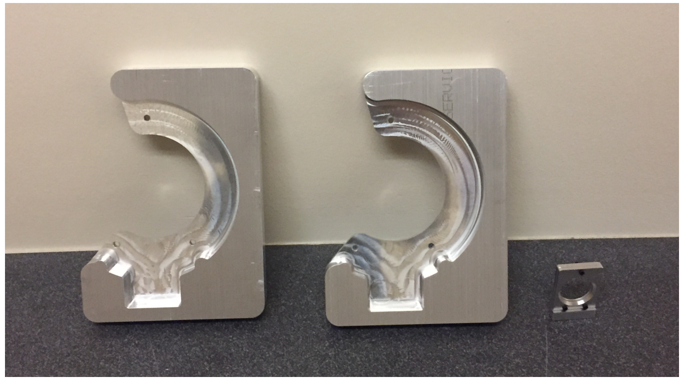
List of state parameters

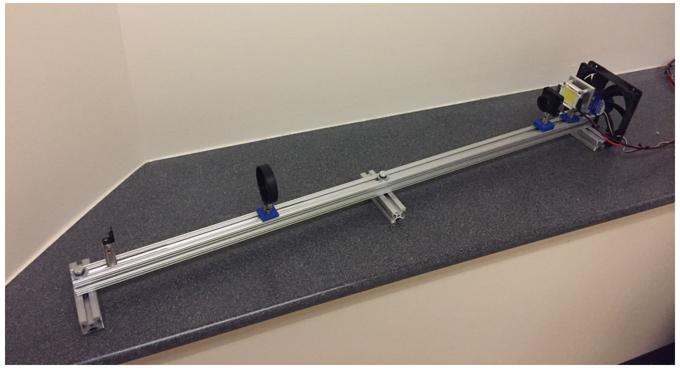
```
# RCWS EXPT (us), SHA EXPT (us), RCWS D FORE
0.0166666667, 0.0166666667, 500, 500, 0, 0
0.0083333333, 0.0083333333, 500, 500, 0, 0
0.0166666667, 0.0166666667, 1500, 1500, 0, 0
0.0083333333, 0.0083333333, 1500, 1500, 0, 0
0.0166666667, 0.0166666667, 2500, 2500, 0, 0
0.0083333333, 0.0083333333, 2500, 2500, 0, 0
0.0166666667, 0.0166666667, 500, 500, 0, 100
0.0083333333, 0.0083333333, 500, 500, 0, 100
```

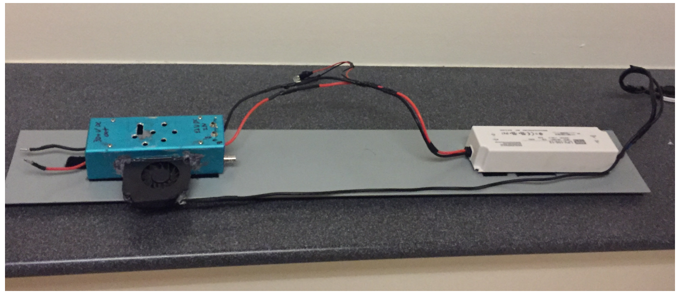
3.1 – Progress Since MSR
3.2 – Overview Moving Forward
3.3 – Testing Schedule

3.0 – SCHEDULE

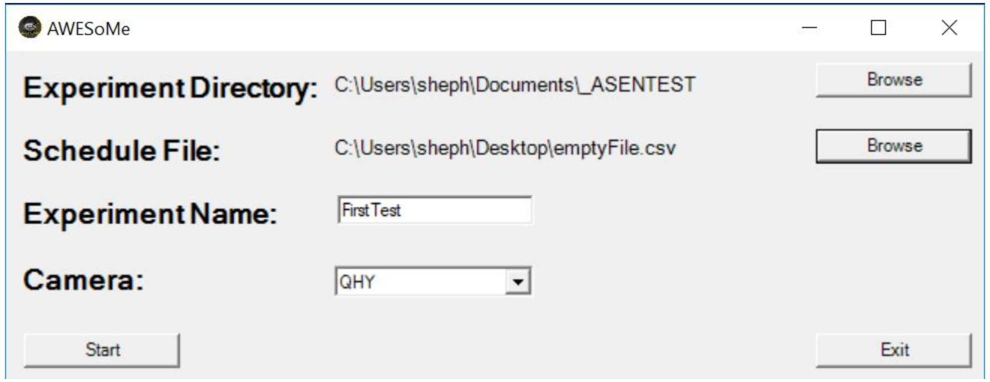
3.1 – Progress Since MSR

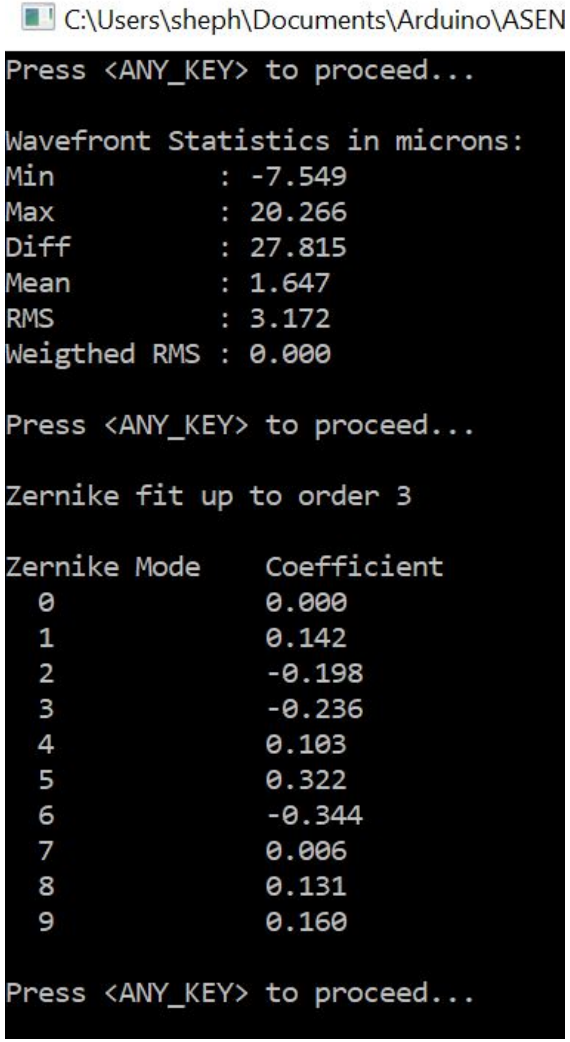




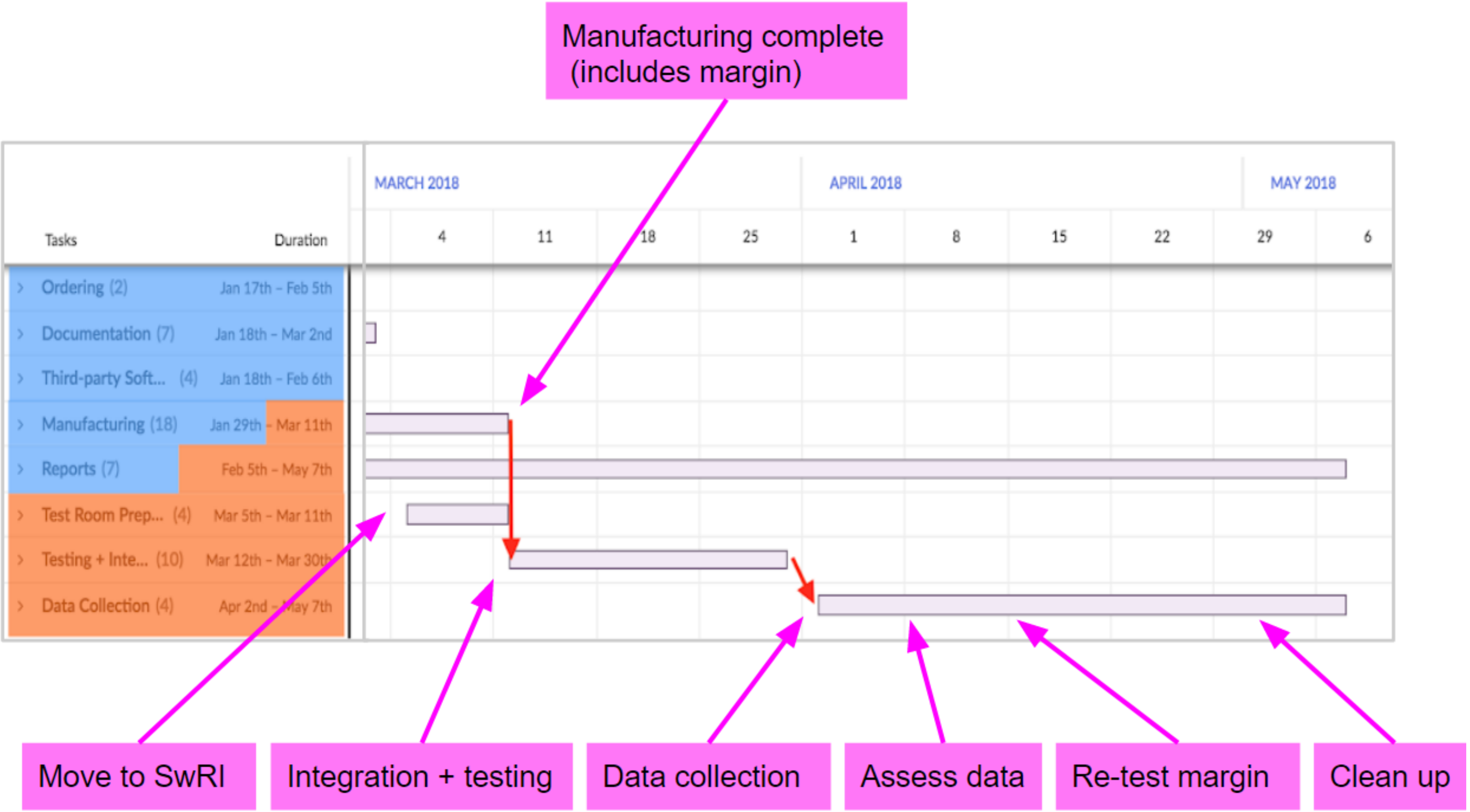


- Manufactured Mirror Mounts
- Manufactured Pellicle Mount
- Setup and Baseline Testing of Image Source
- All APIs have been tested
- Currently writing a main program to interface with the controllers and sensors

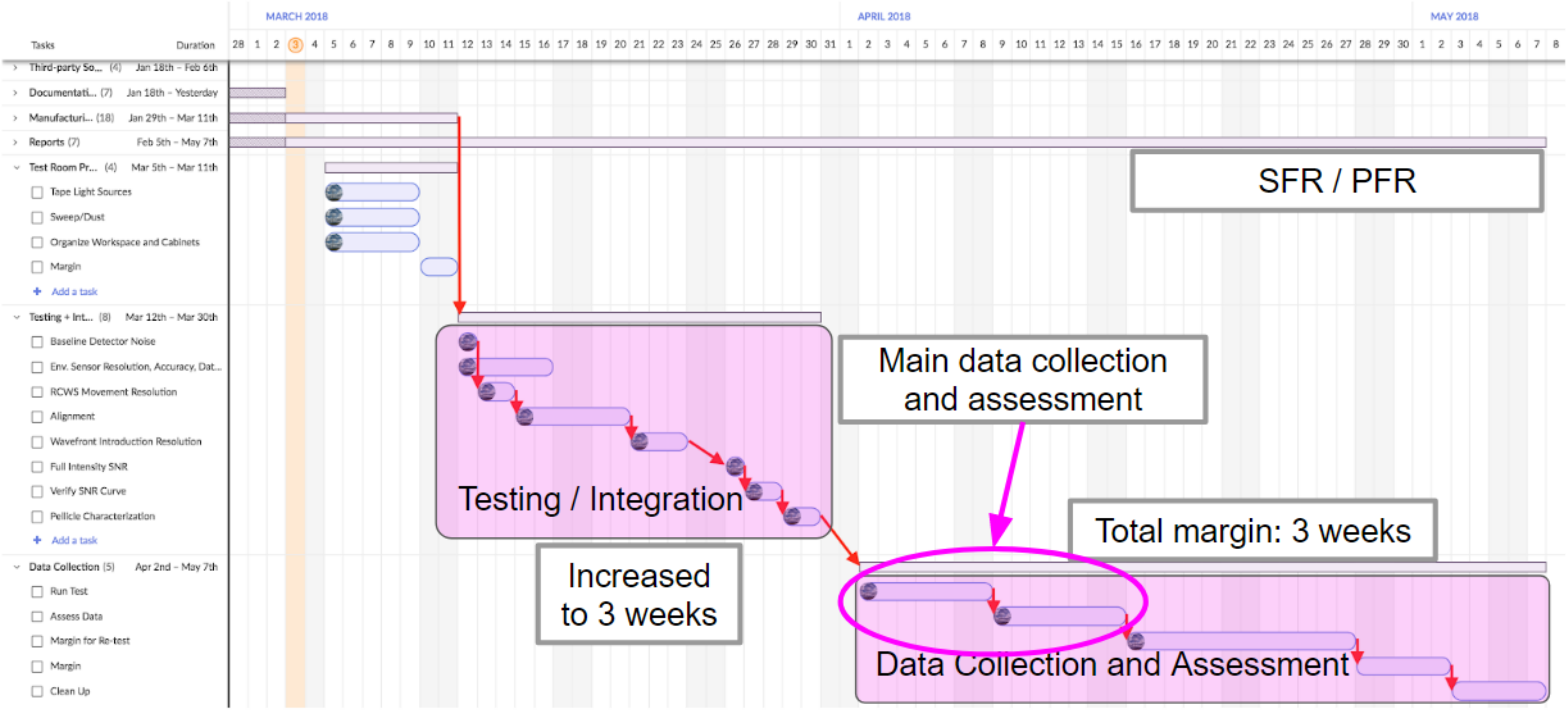




3.2 – Overview Moving Forward



3.3 – Testing Schedule



4.1 – Budget Overview & Ordering Status

4.0 – BUDGET

4.1 – Budget Overview & Ordering Status

	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	$ 4,570.07	57.13%
	SwRI/NASA Glenn	$ 5,379.15	100.00%

Class + EEF Funding:

- 57.13% spent
- $3,429.93 remaining, to be used to purchase additional test equipment and cover accidental loss of optical components

Resources on Loan:

- ThorLabs Shack-Hartmann Array
- QHY CMOS detector
- ThorLabs motorized stages
- Lab space

Ordering:

- All planned items have been ordered

Pending receipt:

- Gloves
- Masks
- Lasers
- Neutral Density Filter

Thank you for listening!

QUESTIONS?

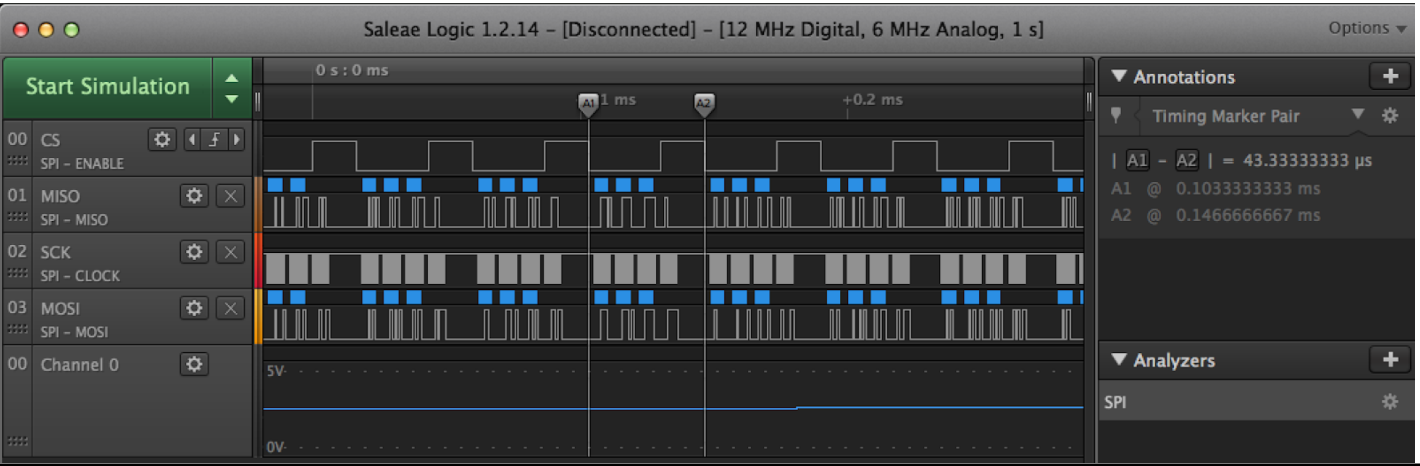
BACKUP SLIDES

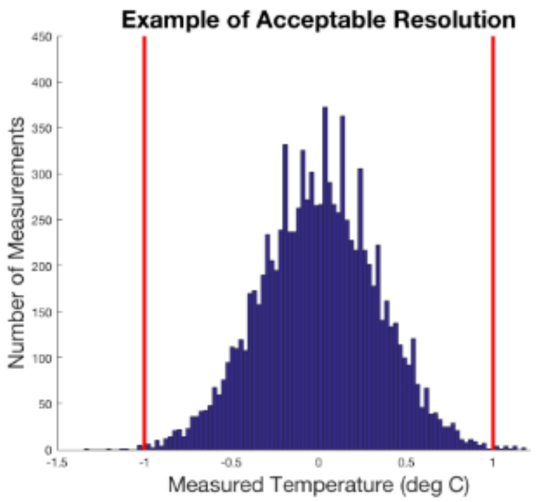
Accelerometer Data Rate

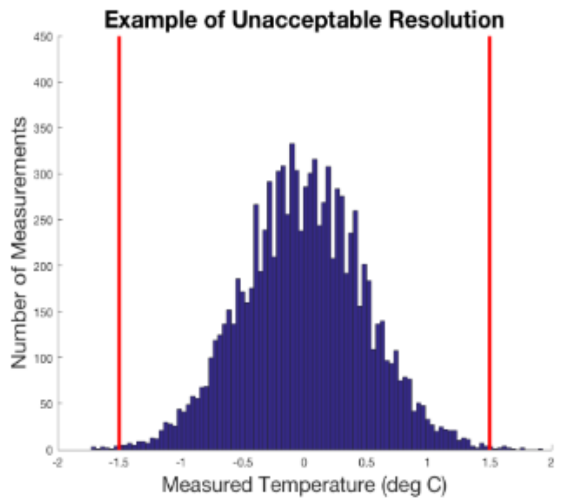
- Ensure 1 kHz timing precision in sampling from accelerometers
- Performed by monitoring chip select lines of all 6 accelerometers with a digital logic analyzer
- Ensures that variations in sampling rate do not affect vibrational measurements

Temperature Resolution

- 1°C resolution required to determine 1% change in RMS wavefront error, accuracy is inconsequential
- Tested by maintaining sensors at 0°C in ice-water slurry, determine fraction of measurements within required bounds

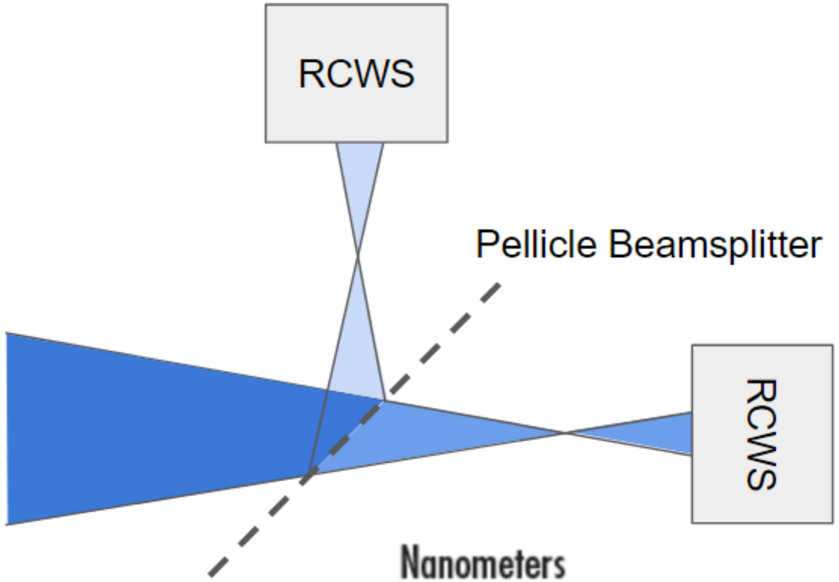


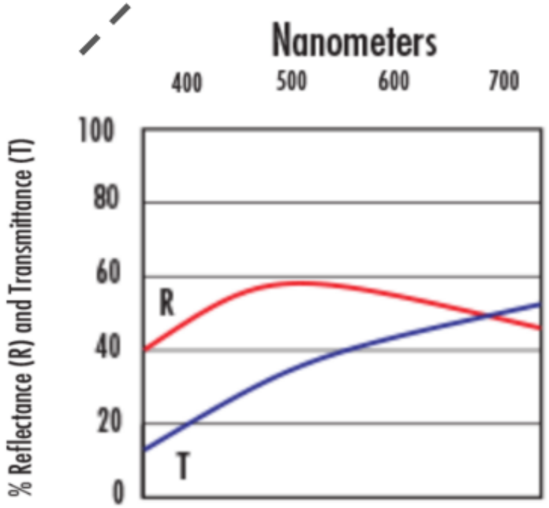




Pellicle Characterization

- Want to determine transmission/reflection properties of pellicle beamsplitter
- Allows for received intensity correlation during data collection
- Performed by placing RCWS detector at two locations to measure the intensity of received light on both sides of the pellicle

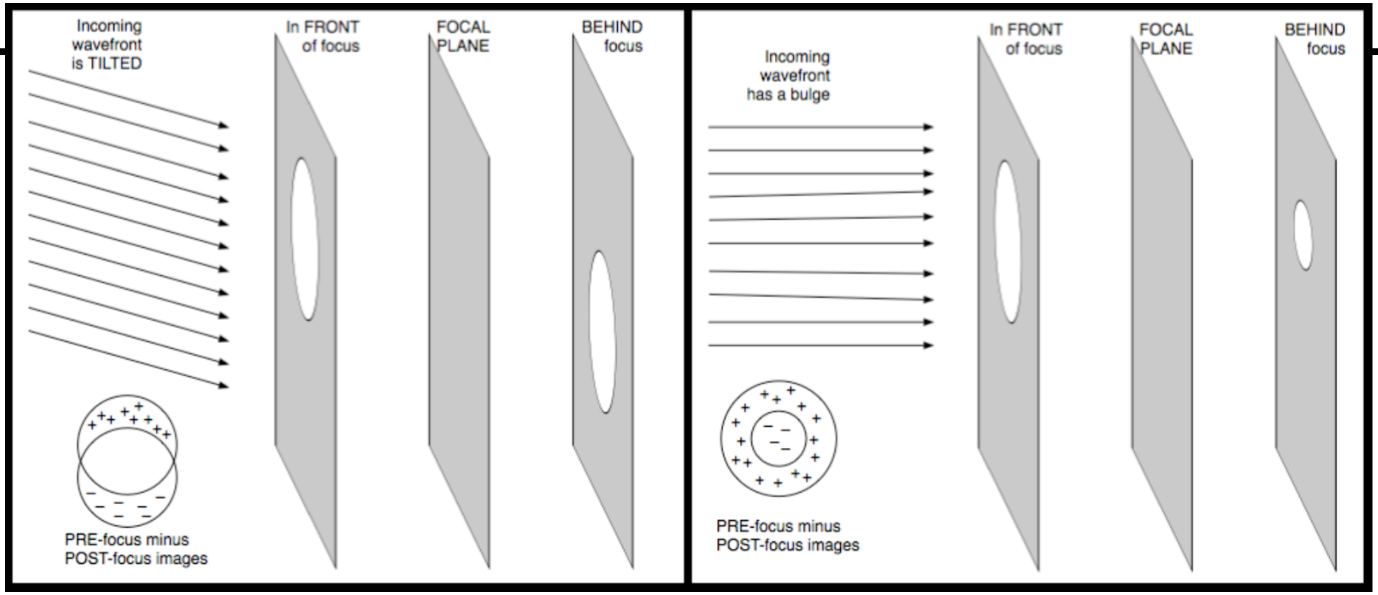




Software Verification

Zemax Model	Forward-Predictive Model	RCWS Algorithm
Purpose: prove that the optical model in Zemax predicts the performance of the physical system	**Purpose:** ensure that the defocused images generated by the Forward-Predictive model are similar to the physical results	**Purpose:** Determine performance of RCWS algorithm, independently of the detector used
Method: Compare SHA measured wavefront changes to those predicted in Zemax	**Method:** Find difference between defocused images from RCWS detector and Forward-Predictive model simulation	**Method:** Feed algorithm with simulated images from the Forward-Predictive model, which can be use significantly more resolution and contain much lower noise

RCWS: Transport of Intensities (TIE)



TIE: Association between image intensity (LHS) and wavefront (RHS)

$$\frac{I_- - I_+}{I_- + I_+} = \frac{f(f-\ell)}{\ell}\left\{\nabla^2 z - \delta_b \frac{\partial z}{\partial n}\right\}$$

Local curvature produces difference in intensities.
Slope at edges produces different widths in the image.

Finite Differences Solver

- Method to solve for the wavefront as a grid of discrete values
- Represent the normal derivative and the laplacian operator as linear combinations of grid values
- Then, have a system of linear equations
  - Solve matrix equation
  - If overdefined use regression analysis
- Other methods (FFT, Zernike matrix) are more efficient computationally, but require multiple iterations to converge and are more complicated

$$\frac{u(x-h,y)+u(x+h,y)-4u(x)+u(x,y-h)+u(x,y+h)}{h^2}$$

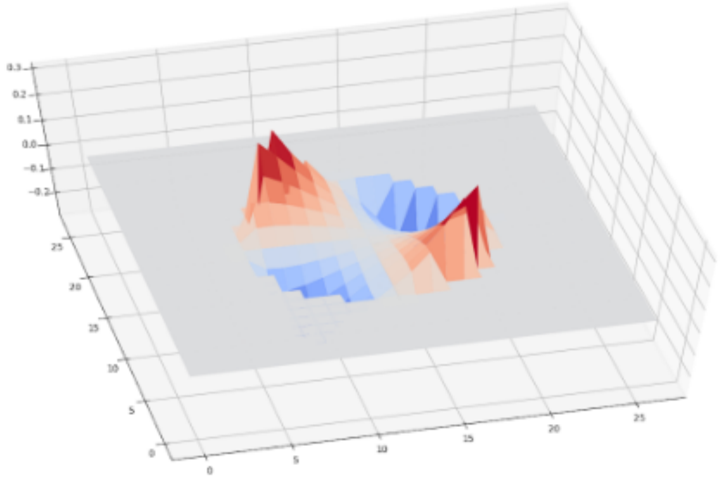
Laplacian operator

$$\frac{u(x+h)-u(x)}{h}$$

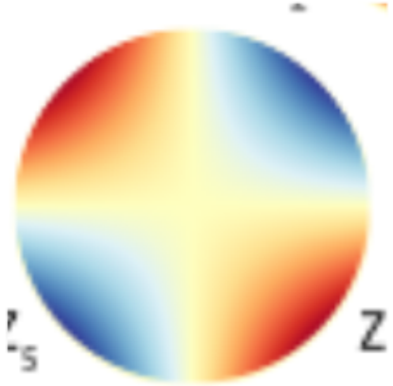
Normal Derivative

Finite Differences Results

- Correct form, i.e. astigmatism comes out saddle shaped
- Magnitude has not been verified, due to difficulty validating forward model
    - Two different magnitudes:
        - Magnitude of Laplacian
        - Magnitude of Normal Derivative
- Needs to be tested and tuned with experimental data from testbed



Reconstructed Wavefront



Astigmatism Mode

Tilt/Tip Platform Uncertainty Calculations

Equation to calculate angle from image displacement

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

Propegating the uncertiainty

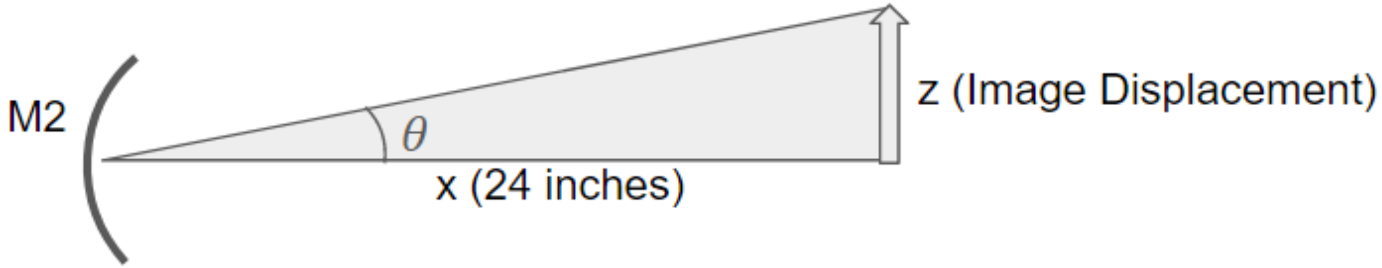
$$(\delta\theta)^2 = \left(\frac{\partial\theta}{\partial x}\right)^2 (\delta x)^2 + \left(\frac{\partial\theta}{\partial z}\right)^2 (\delta z)^2$$

Where:

$$\frac{\partial\theta}{\partial x} = \frac{-z}{z^2 + x^2} \qquad \frac{\partial\theta}{\partial z} = \frac{x}{z^2 + x^2}$$

Therefore

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



Assuming:

$$x = 24\ in = 0.6096\ m$$

$$\delta z = 1.465 \times 10^{-6}\ m$$

$$\theta = 7.13\ arcsec$$

$$z = x\tan\theta = 2.10722 \times 10^{-5}\ m$$

The following results are obtained:

δx (m)	$\delta\theta$ (arcsec)
0.0254	0.434607
0.01	0.338089
0	0.317213

Linear Stage Uncertainty Calculations

Equation to calculate x-traverse from image displacement

$$\tan\phi = \frac{z}{x} \Rightarrow x = \frac{z}{\tan\phi}$$

Propegating the uncertainty

$$(\delta\ x)^2 = \left(\frac{\partial x}{\partial z}\right)^2 (\delta z)^2 + \left(\frac{\partial x}{\partial \phi}\right)^2 (\delta\phi)^2$$

Where:

$$\frac{\partial x}{\partial z} = \frac{1}{\tan\phi} \qquad \frac{\partial x}{\partial \phi} = \frac{-z * \sec^2\phi}{\tan^2\phi}$$

Therefore

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

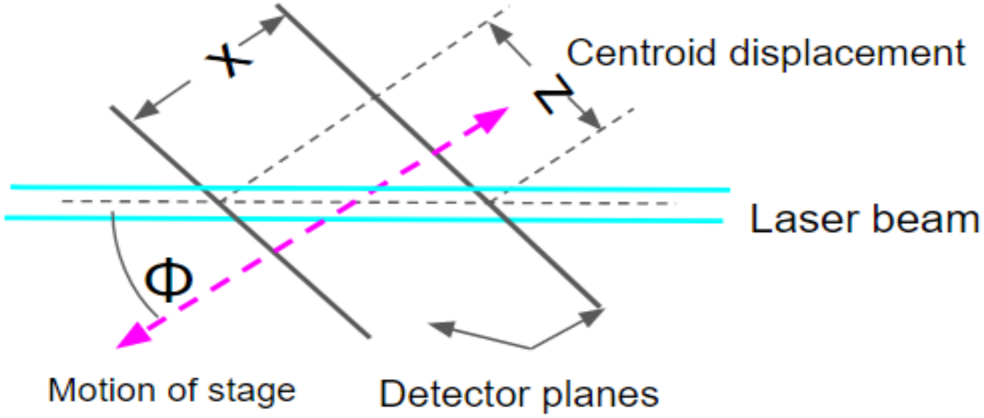
Assuming

$$\delta z = 1.465 \times 10^{-6}\ m$$

$$\phi = 45^\circ$$

$$x = 1 \times 10^{-3}\ m$$

$$z = x\tan\theta = 2.10722 \times 10^{-5}\ m$$



$\delta\Phi$ (°)	δx ($\times 10^{-6}$ m)	% Uncertainty ($100 \times \delta x/x$)
5	174.5	17.45
2	69.82	6.982
1	34.92	3.492
0	0.9375	0.09375

Schedule Dates

Begin Date	Description
March 5th	Move into SwRI lab, organize and prepare for integration
March 12th	Begin integration and subsystem verification
April 2nd	Begin data collection experiment
April 9th	Assess data
April 16th	Begin retest margin
April 30th	General margin, clean up and leave lab space