Apparatus for Wavefront Error Sensor Measurement (AWESoMe) PDR

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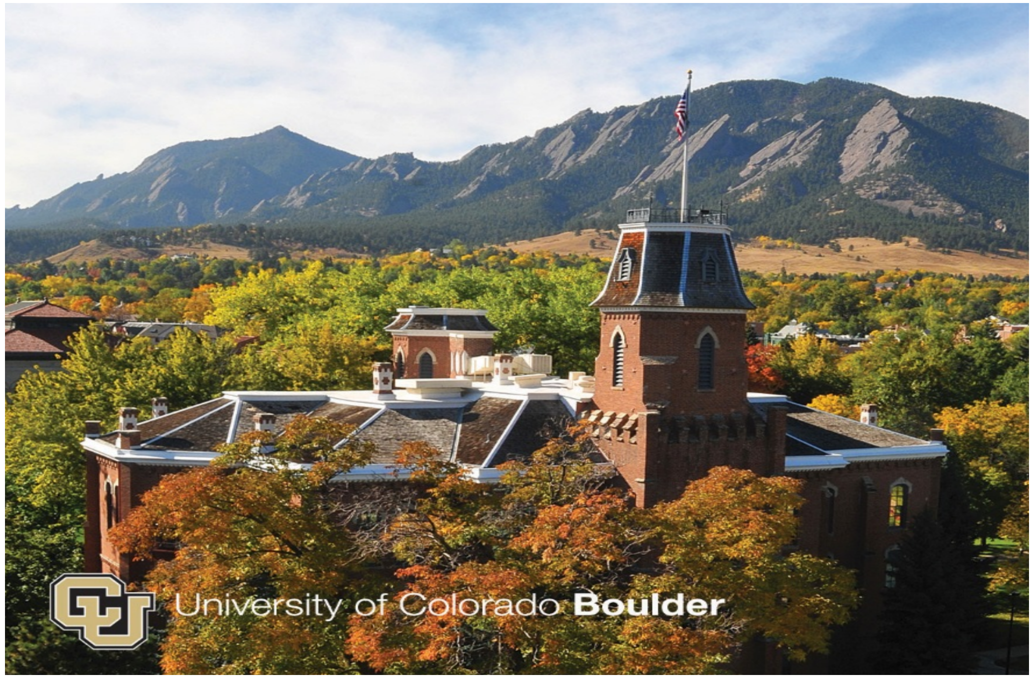
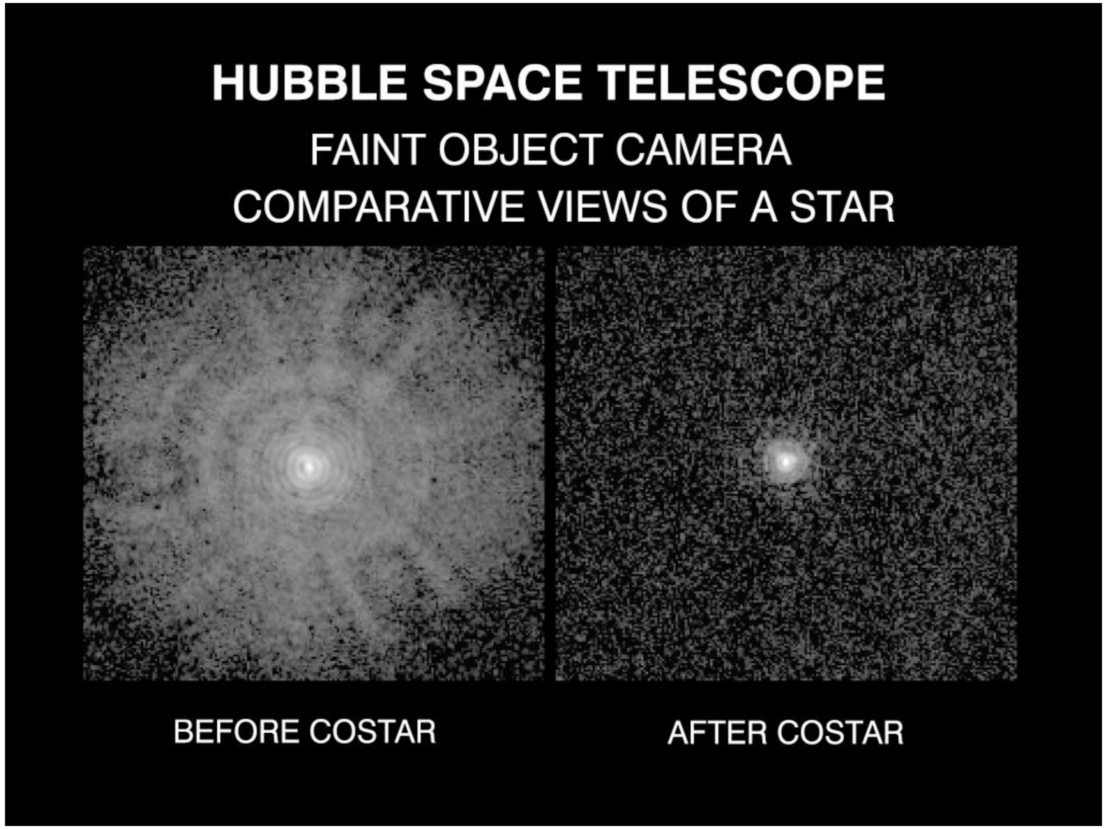
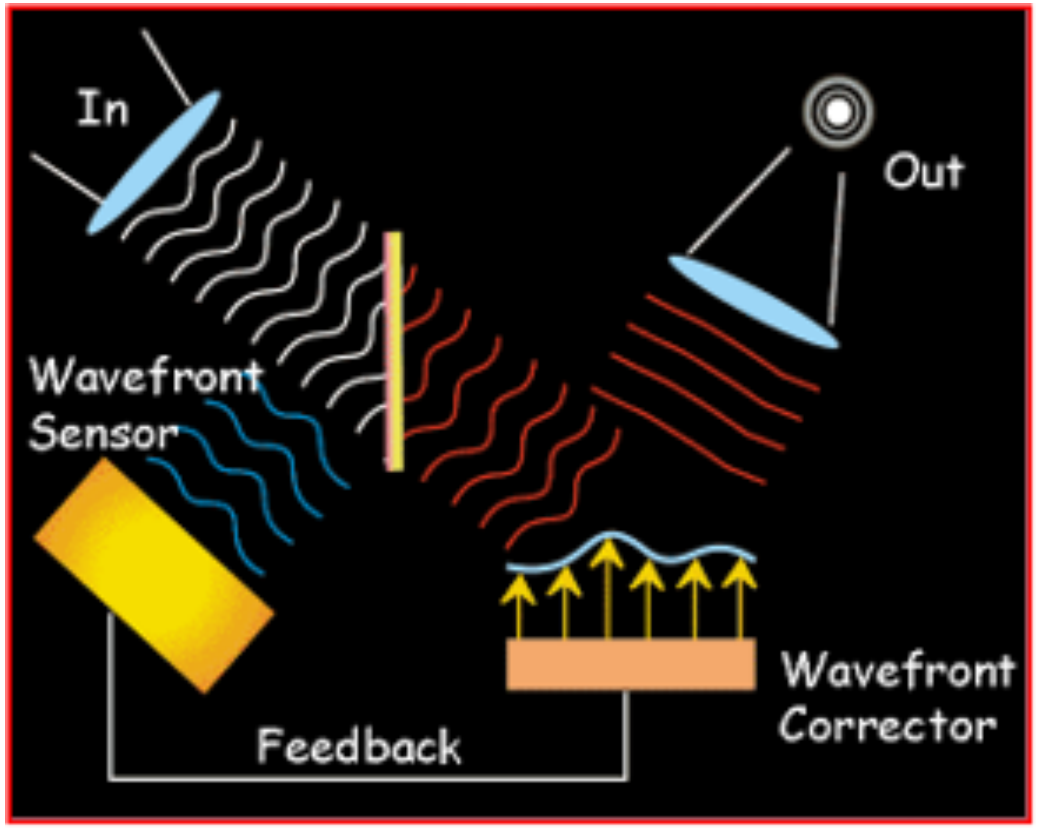


1 - Introduction



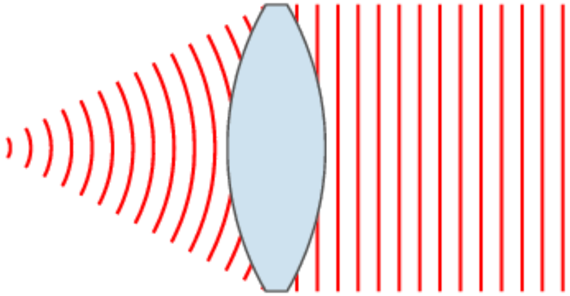
Optical systems are susceptible to small errors imparted from the environment and the tolerances in the system



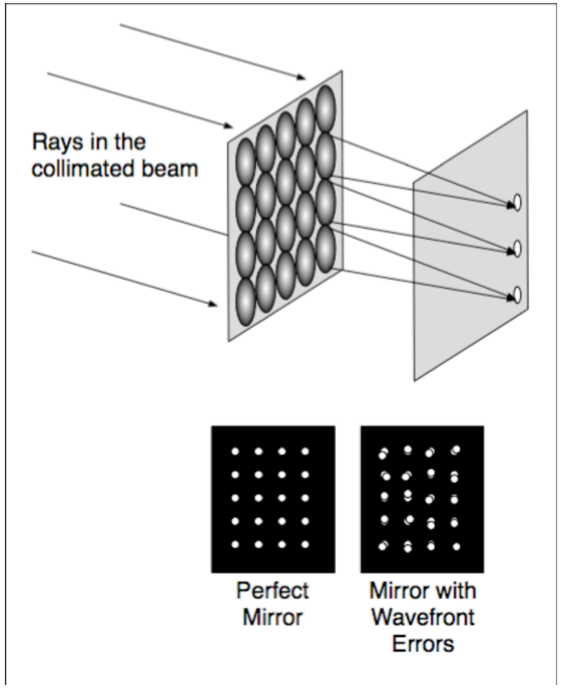
Active optics (AO) uses wavefront measurements to correct optical systems

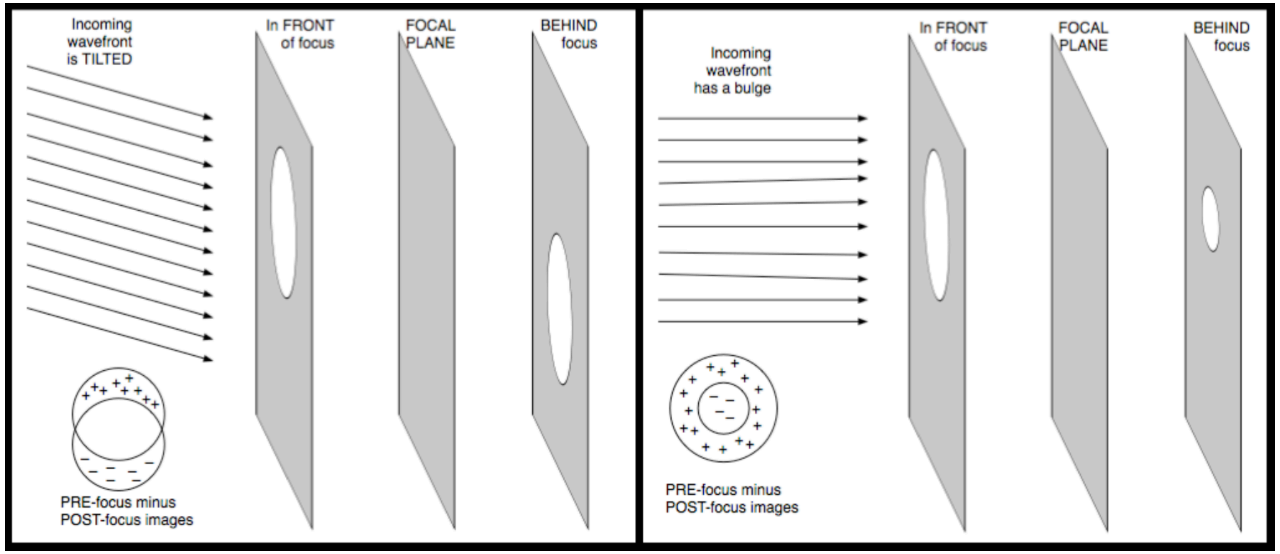
Wavefront Sensors

- 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)



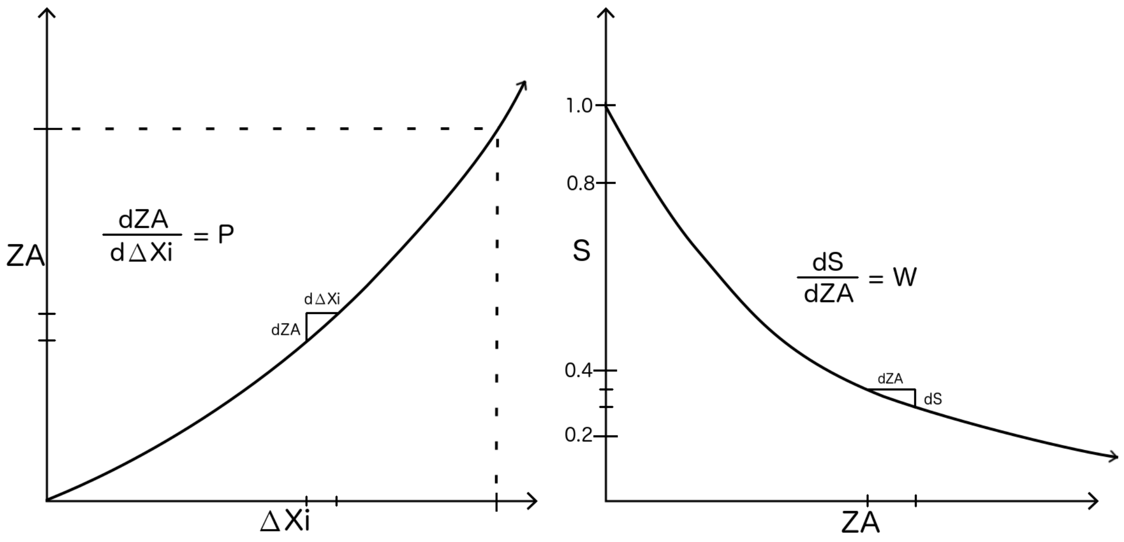


Roddier Method (Left)

1.1 - Project Brief

- Compare the performance of the SHA and RCWS methods as a function of source intensity

- **Sensor characterization metrics:**
  - Response of change in measured error to introduced error
  - Time required to determine wavefront error

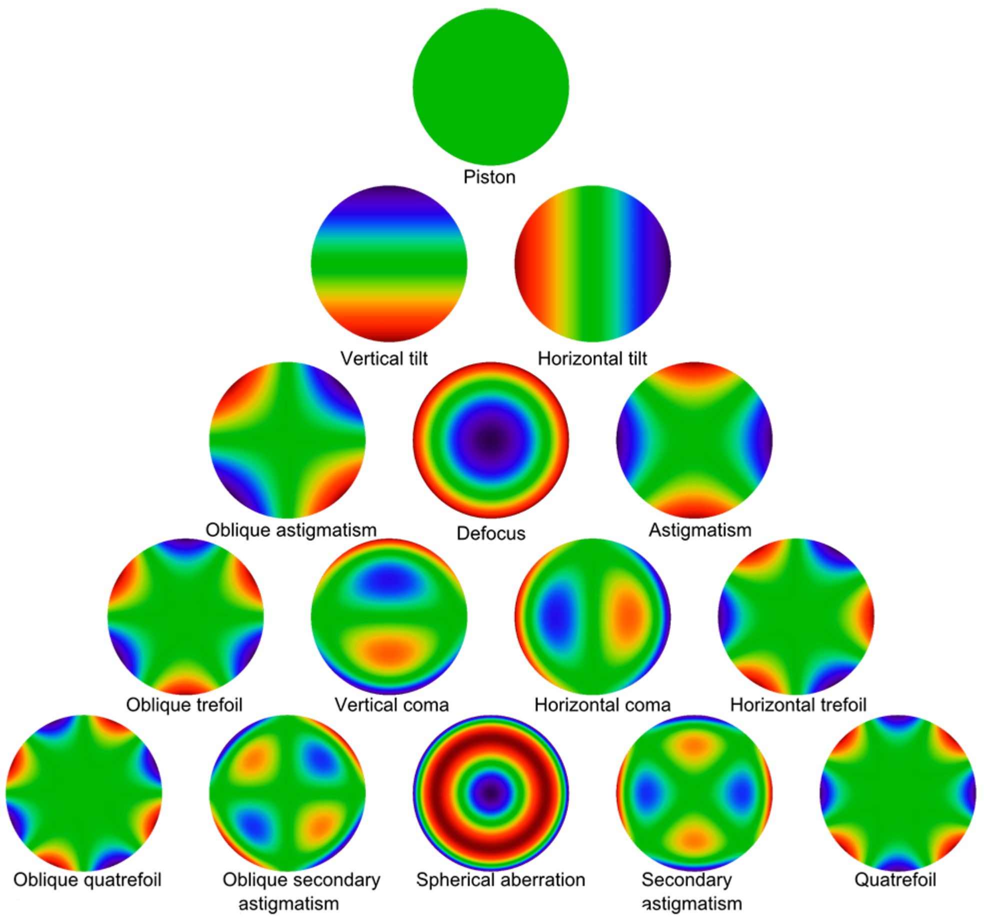


$$d\Delta X_i = \frac{dS}{W \cdot P}$$

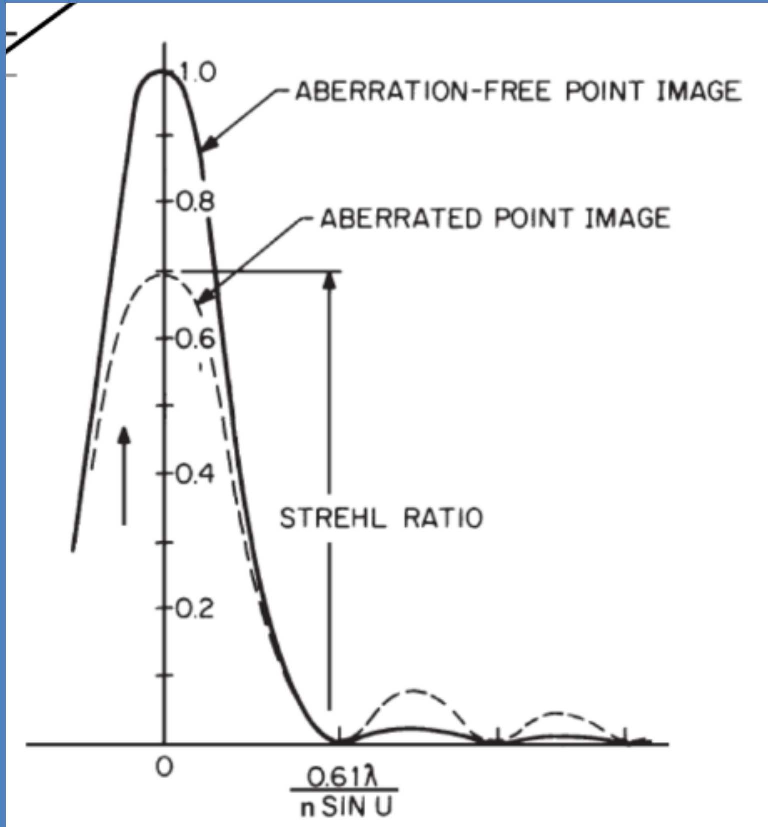
Zernike Polynomials

- **Characteristics:**
  - A complete set of orthogonal polynomials that arise in the expansion of a wavefront function for optical systems with circular pupils. [1]
  - 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



Strehl Ratio

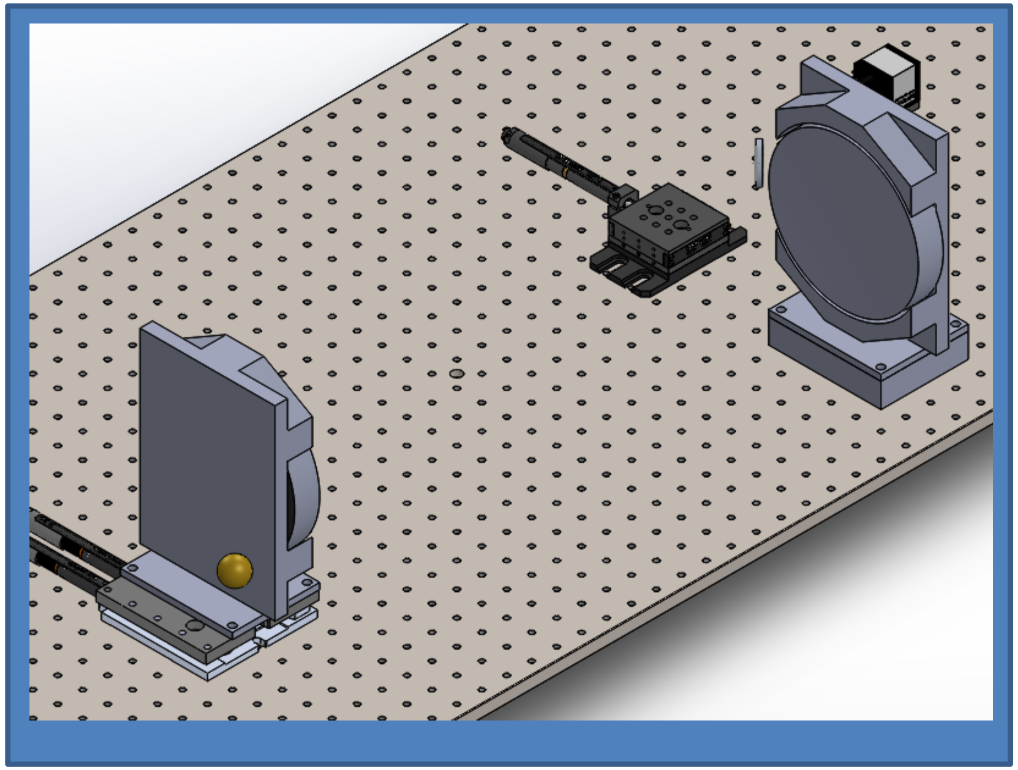


Modern Optical Engineering, Smith

- **Characteristics:**
  - Ratio of maximum intensities between aberrated and ideal images
  - Difficult to compute analytically, numerical approximations often used
- **Use in this project:**
  - Represent requirements at high level before final geometry chosen.
  - Modelled in Zemax and IPython to guide design
  - Not computed or used beyond design

1.1.1 - Objectives

- Develop a forward-predictive model to drive design and validate results
- Develop an RCWS and accompanying algorithm to be used on the testbed
- Develop a test platform capable of providing the required data
- Present findings from one set of tests



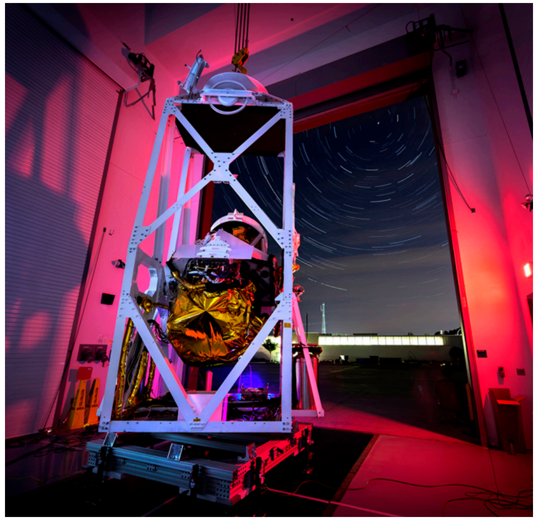
Approximate position of mirrors on testbed

Motivation

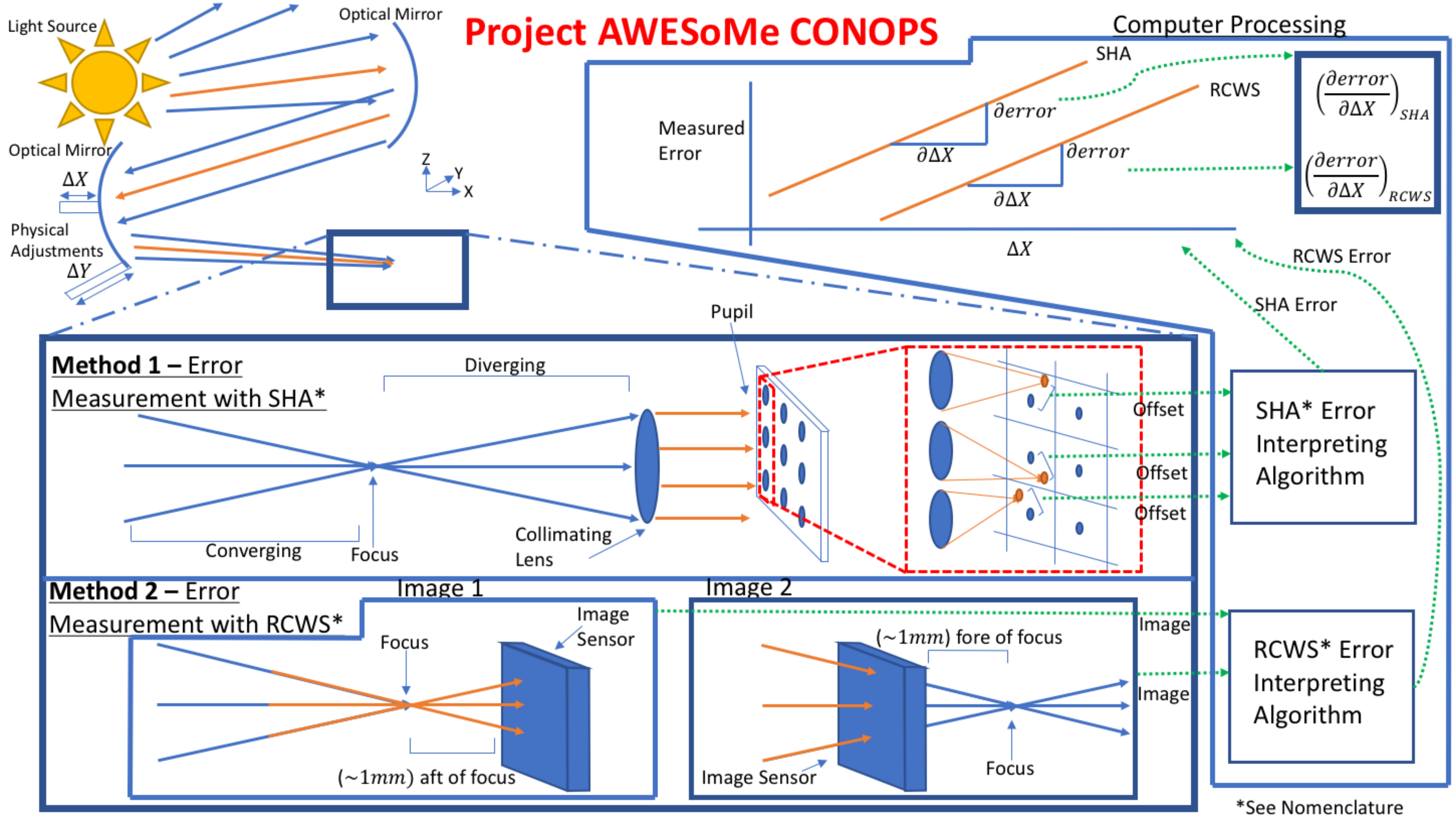
Potential benefits of RCWS:

- 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

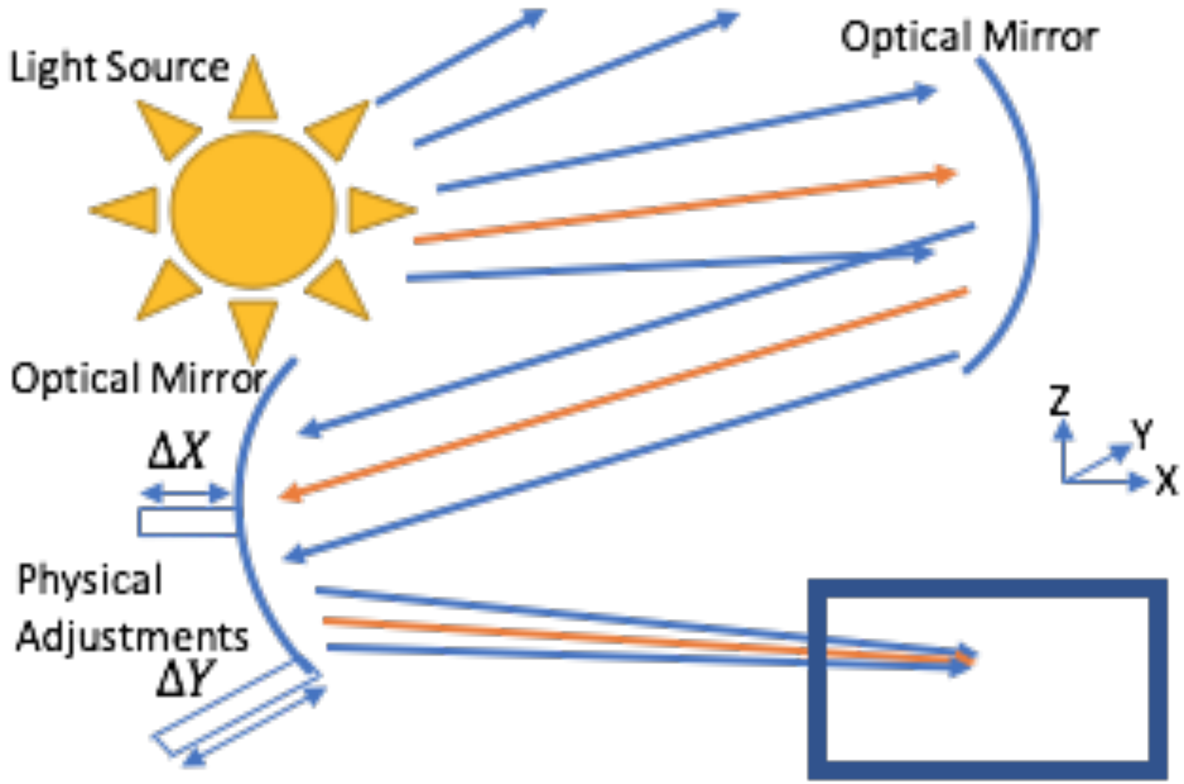


1.1.2 - CONOPS

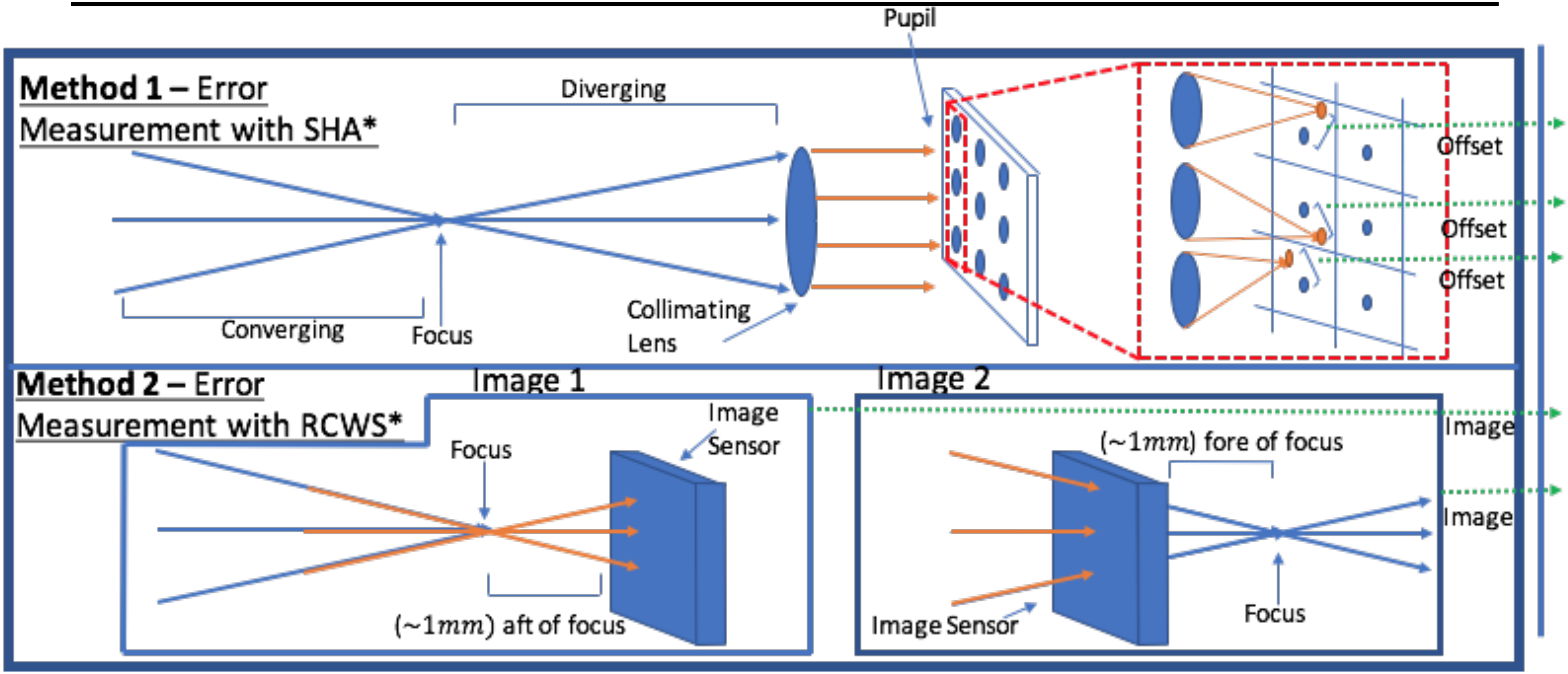


*See Nomenclature

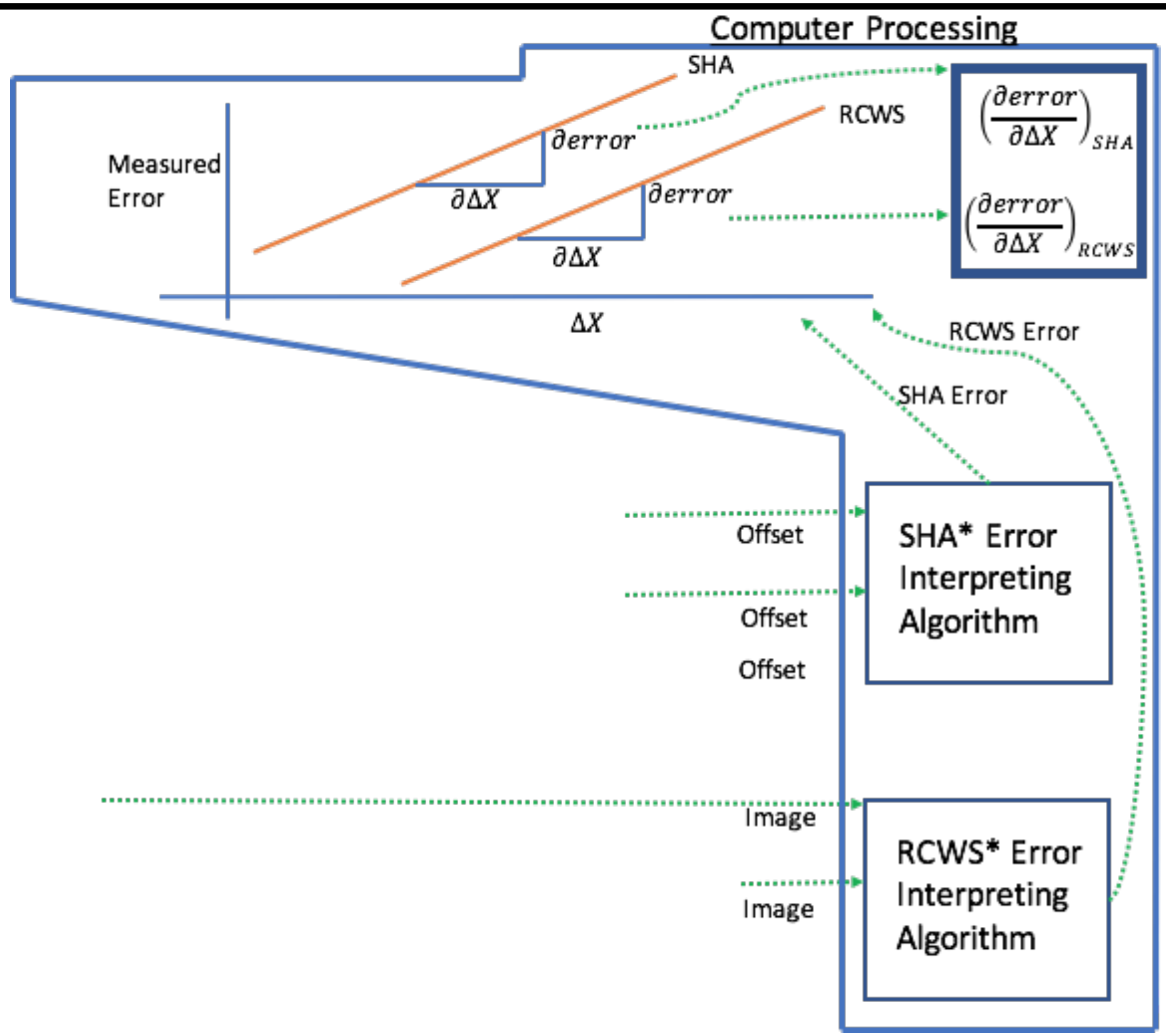
CONOPS Part 1



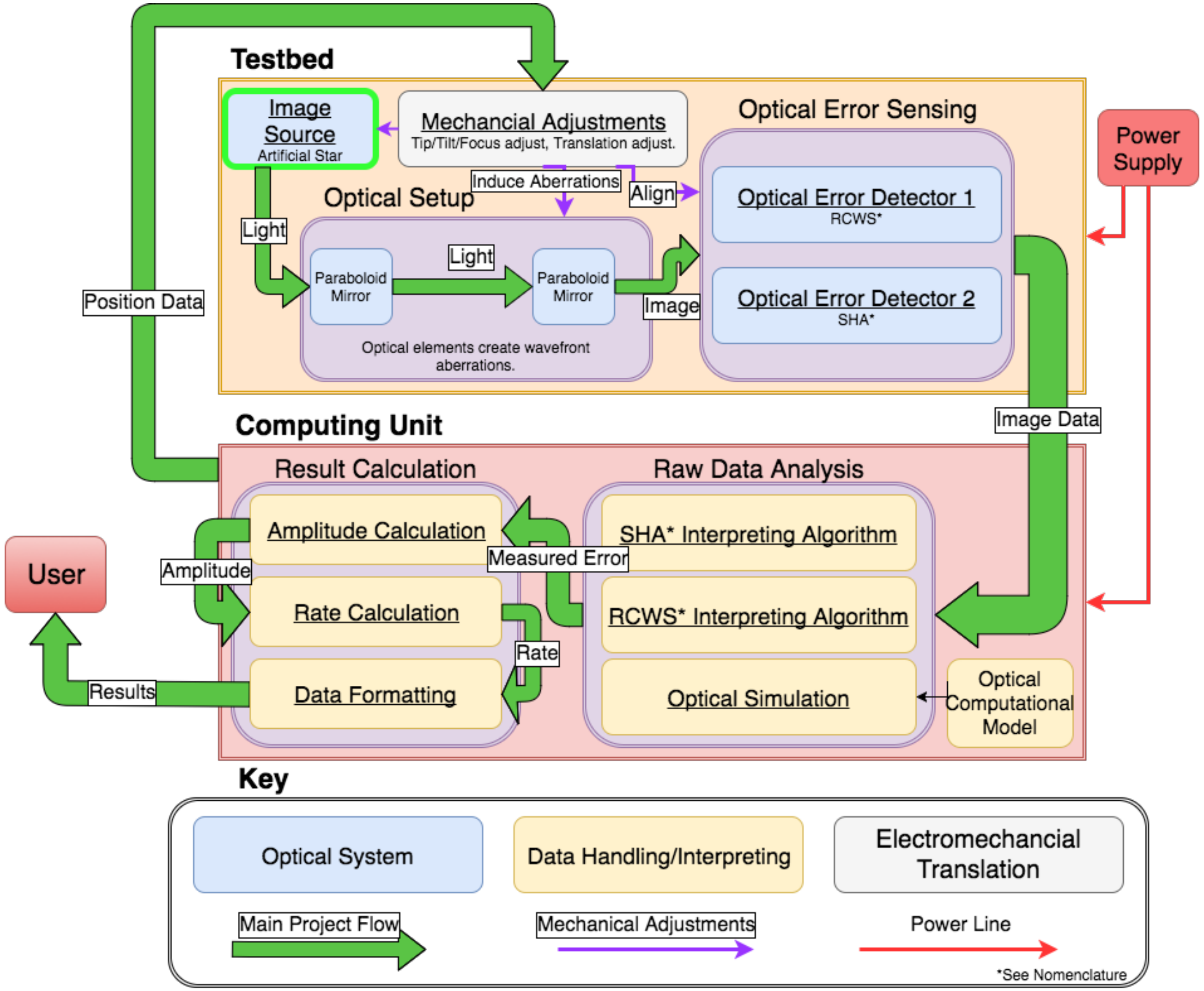
CONOPS Part 2



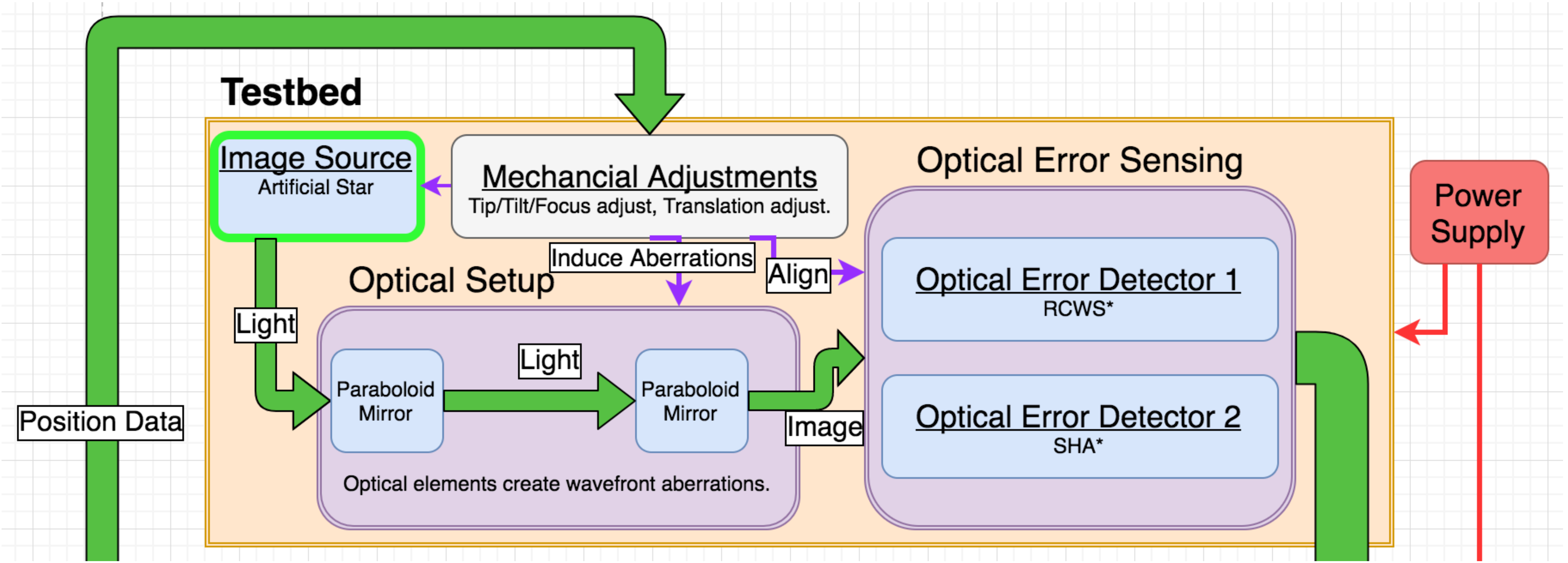
CONOPS Part 3



1.1.3 - FBD


Testbed
Image Source
Artificial Star
Mechancial Adjustments
Tip/Tilt/Focus adjust, Translation adjust.
Optical Error Sensing
Induce Aberrations
Align
Optical Setup
Light
Light
Paraboloid Mirror
Paraboloid Mirror
Image
Optical elements create wavefront aberrations.
Optical Error Detector 1
RCWS*
Optical Error Detector 2
SHA*
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
User
Results
Data Formatting
Optical Simulation
Optical Computational Model
Key
Optical System
Data Handling/Interpreting
Electromechancial Translation
Main Project Flow
Mechanical Adjustments
Power Line
*See Nomenclature

FBD Part 1



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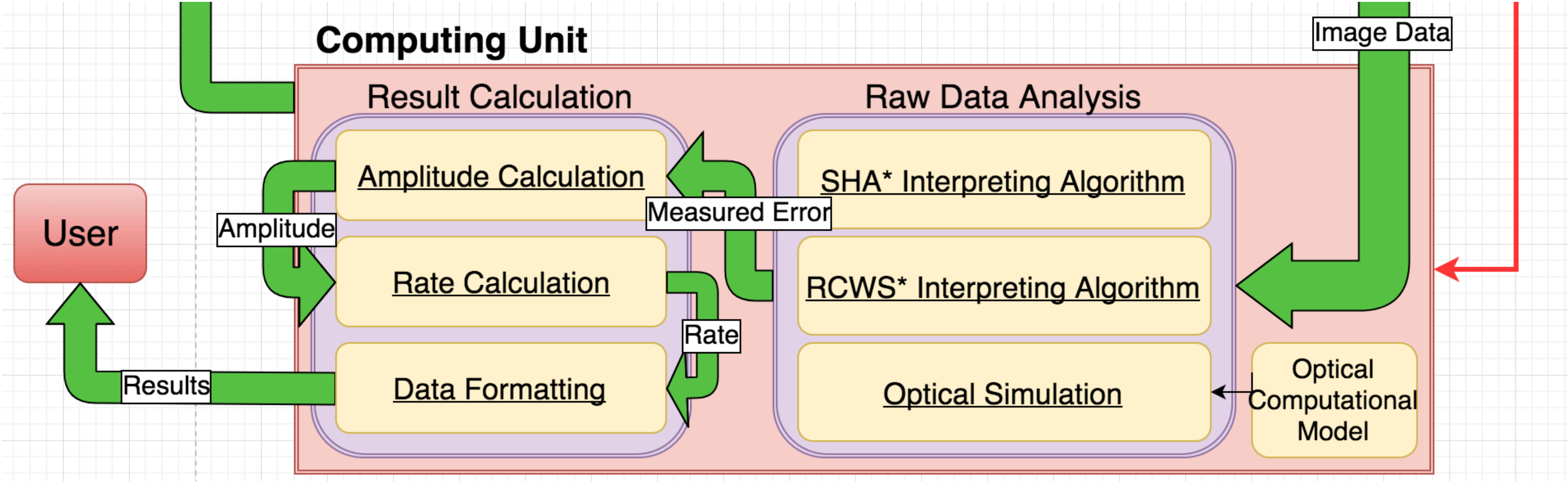
FBD Part 2

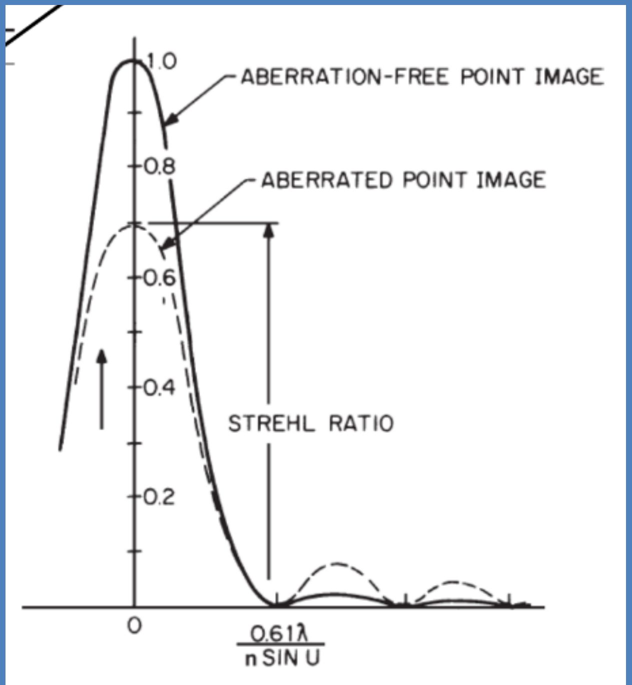


Computing Unit
Image Data
Result Calculation
Raw Data Analysis
Amplitude Calculation
SHA* Interpreting Algorithm
Measured Error
User
Amplitude
Rate Calculation
RCWS* Interpreting Algorithm
Rate
Results
Data Formatting
Optical Simulation
Optical Computational Model

1.1.4 Requirements

- **Functional Requirements:**
  - Use a controlled source to feed the system a known image
  - Introduce known errors to the wavefront before it reaches either sensor
  - Measure the wavefront error with both a SHA and RCWS sensor
  - Compare the response rate of measured to introduced errors between the sensors and a simulation.
  - Validate test results by simulation and test environment characterization

- Design requirements given in terms of the **Strehl Ratio** of the system.
- Once more design possibilities are constrained these values can be translated to standard units via simulation in Zemax.



Modern Optical Engineering, Smith

Strehl ratio (above) used as stand-in numerical requirement until design further refined.

Credit: Brian Catanzaro, Thomas Brooks, Bob Woodruff, Brian O'Connor, Will Johnson, Adam Burt

PDR Outline

Presentation Structure

1. Baseline Design
   - Designs from CDD.
2. Key CPEs and Feasibility Studies
   - Key points to be addressed in order to determine feasibility.
   - Evaluation of Key CPEs to reach feasibility.
3. Conclusion and Next Steps

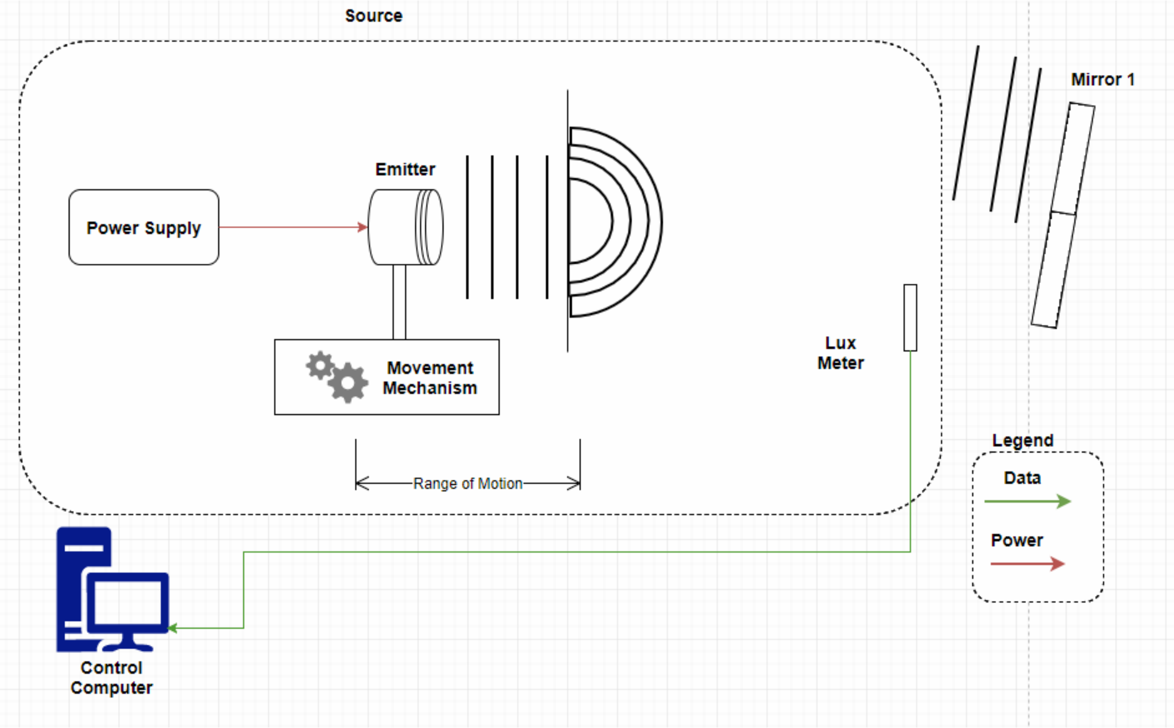
1.2 Baseline Design

Element	Purpose
Image Source	Feed known state to optical system
Optical System	Condition image and introduce known wavefront error
Shack-Hartmann Array	Test Article #1
Roddier Curvature Wavefront Sensor	Test Article #2
Testbed	Align, isolate, and protect optical components
Environmental Sensor System	Validate test conditions
Algorithm and Test Control Software	Compute RCWS Zernike amplitudes, automate test procedure, perform data handling

1.2.1 Image Source

The image source is used to provide a known input to the system.

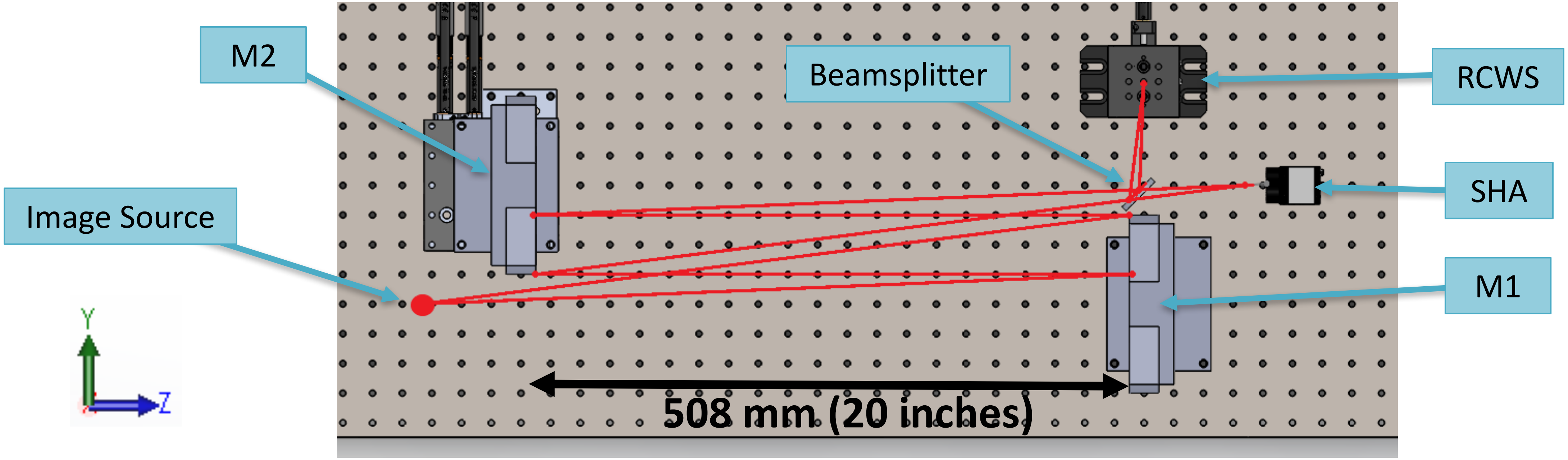
- Both SHA and RCWS require a point source image
- Calculation of wavefront error in RCWS simplified by use of a narrow band of wavelengths
- Image intensity controlled by variable distance from emitter to pinhole aperture
- Incoherent light used to reduce effects of interference
- Source fixed to testbed



1.2.2 Optical System

The optical system conditions the image and introduces known changes in wavefront error.

- Baseline uses 2 degrees of freedom, tip and tilt of mirror 2
- Minimum resolution is 0.06 degrees, 216 arc seconds
- Only alignment of optical axes, not relative translation, matters between mirrors
- Pellicle beamsplitter produces minimal effect on the image, allows simultaneous test of both sensors



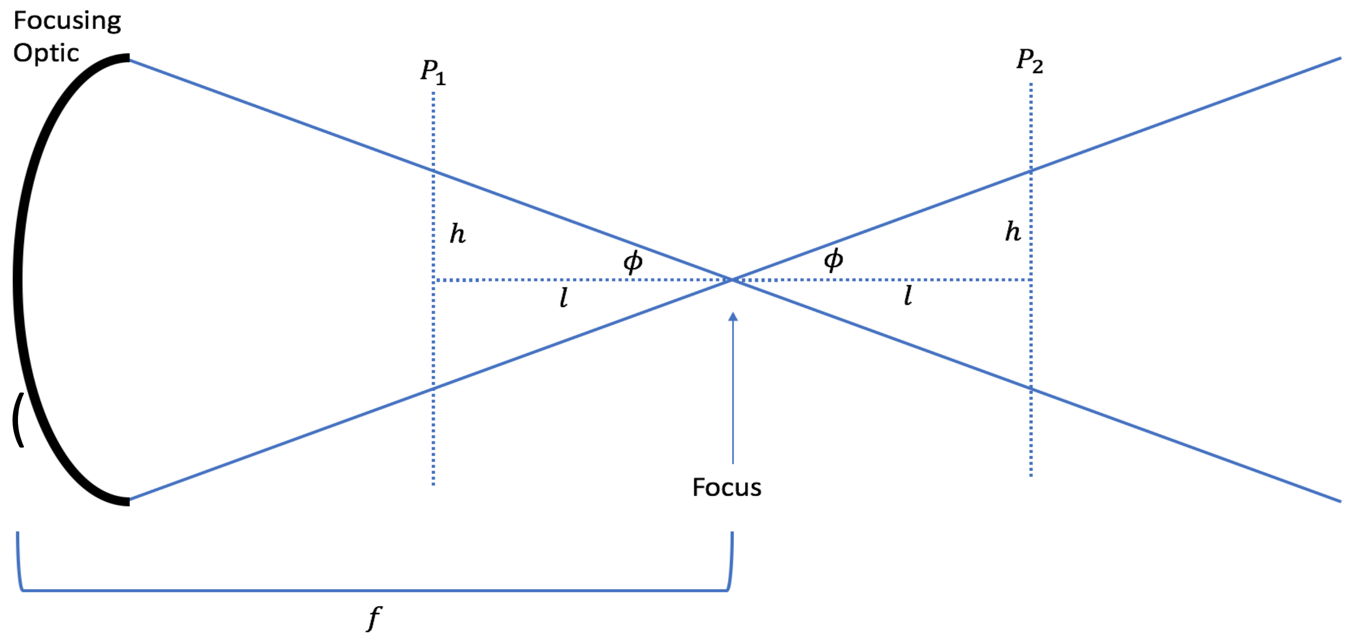
1.2.3 SHA

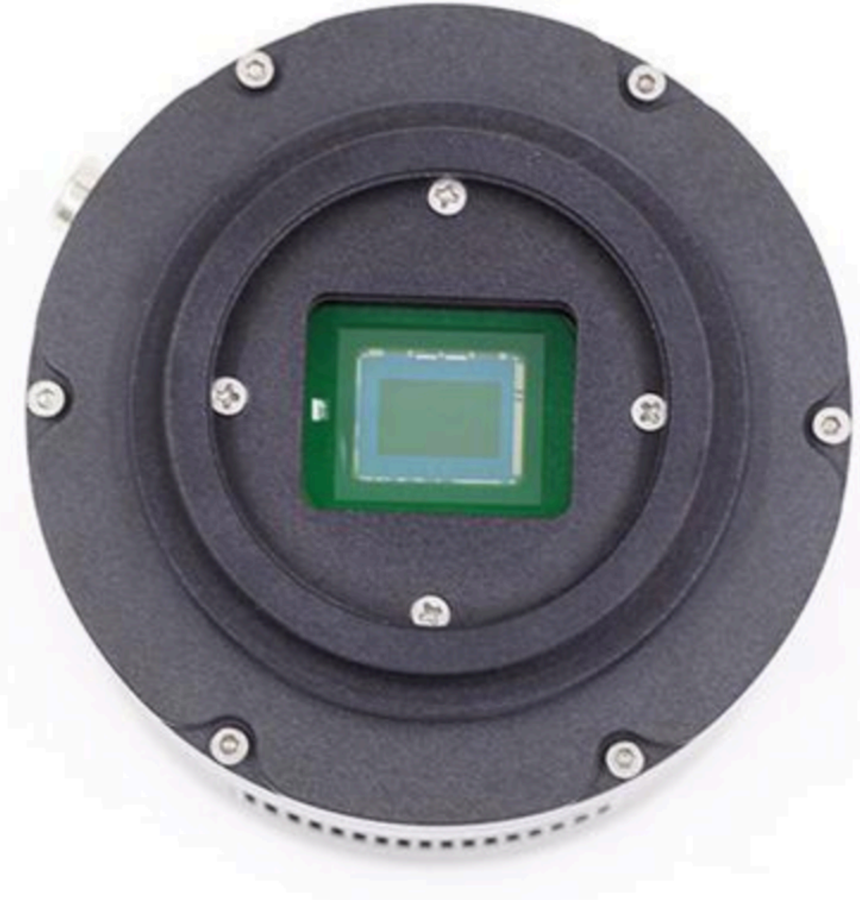
The Shack-Hartmann Array is one of the two test articles.

- An off-the-shelf model from ThorLabs will be provided by the customer.
- Interfaces directly to a Windows PC via USB .
- Software for determining the wavefront error in terms of Zernike coefficients is included.
- Placed in the divergent portion of the optical beam (no collimating lens used) aft of the focus.

1.2.4 RCWS

- A custom RCWS will be developed because no off-the-shelf solutions exist.

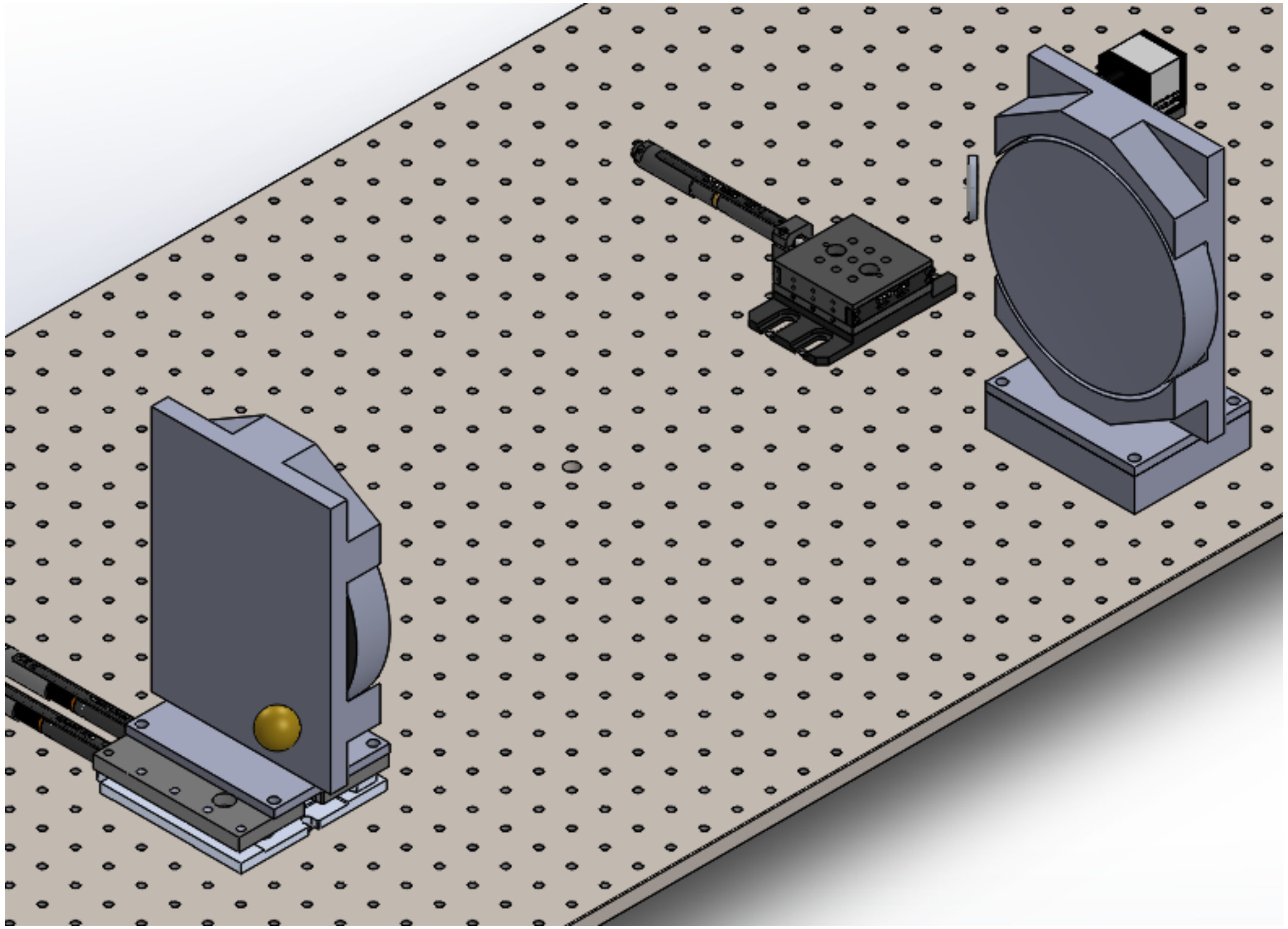




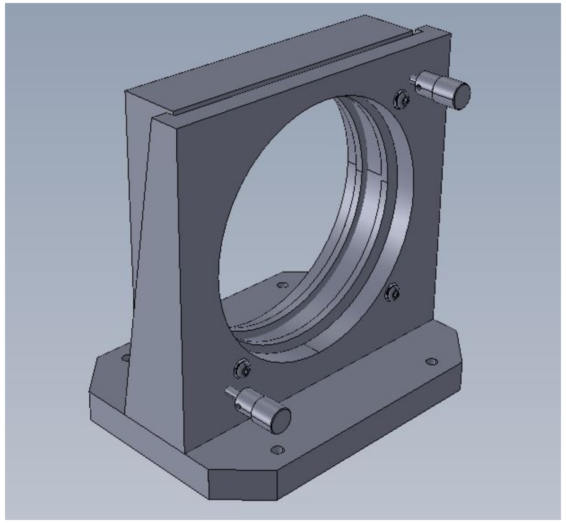
- Use of a single CMOS image sensor.
- Physically translate the CMOS to P_1 and P_2.
- Conduct this linear translation using an optical linear stage.

1.2.5 Testbed

- The image source will be mounted at the focal point of M1
- Mirrors are mounted 20 inches apart face to face and offset by 4 inches between their parabolic axis
- M2 will be mounted on a tilt/tip platform
- The SHA will be mounted behind a pellicle beamsplitter and the RCSW will image on the reflection from the pellicle
- The RCWS will be mounted on the linear traverse in the upper right corner of image



Testbed



The team will be manufacturing custom mirror mounts

- Relatively inexpensive compared to the prebuilt mounts
- Will not block the image source by not wrapping around the mirrors edge

Motorized stages will be used to control the mirror angle and RCWS position

- Removes the human error from adjustments
- Increases repeatability of camera positioning and angle of mirror 2

1.2.6 Environmental Sensors

Purpose:

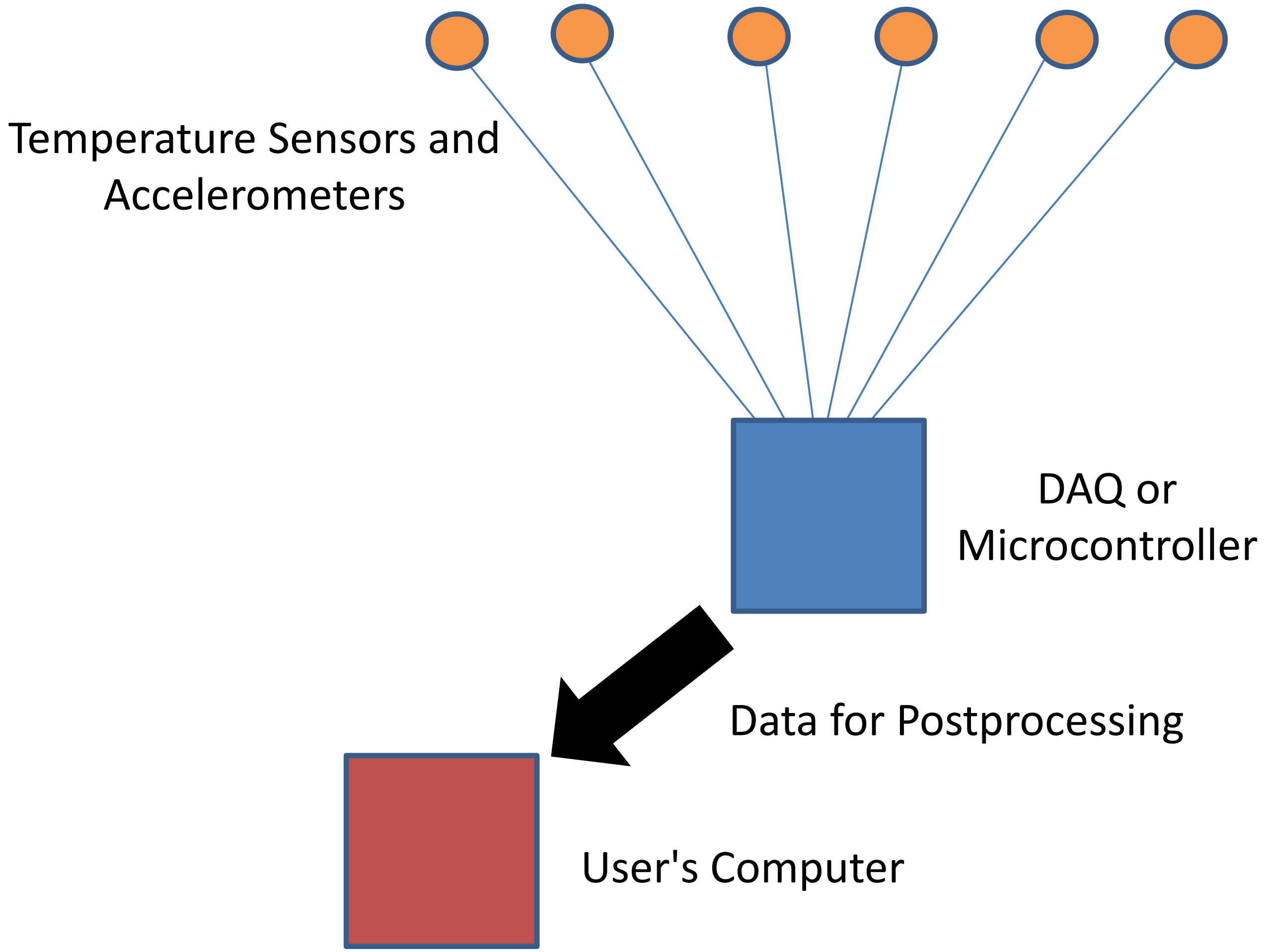
- To validate tests and observe extreme environmental changes

DAQ vs. Microcontroller data collection:

- Data is not required to be live-processed, thus microcontrollers are the cheaper option that achieve desired result.

Digital vs. Analog sensors:

- Cost is not a large driver
- Analog sensors may require signal conditioning (esp. Accelerometers)
- There will be an accelerometer alternative discussed briefly later



1.2.7 Algorithm and Software

Shack Hartman Options Considered:

- ThorLabs has software that meets the requirements of the project (computes desired modes of wavefront error) developed specifically for this sensor
- Developing our own software will likely not result in any better performance

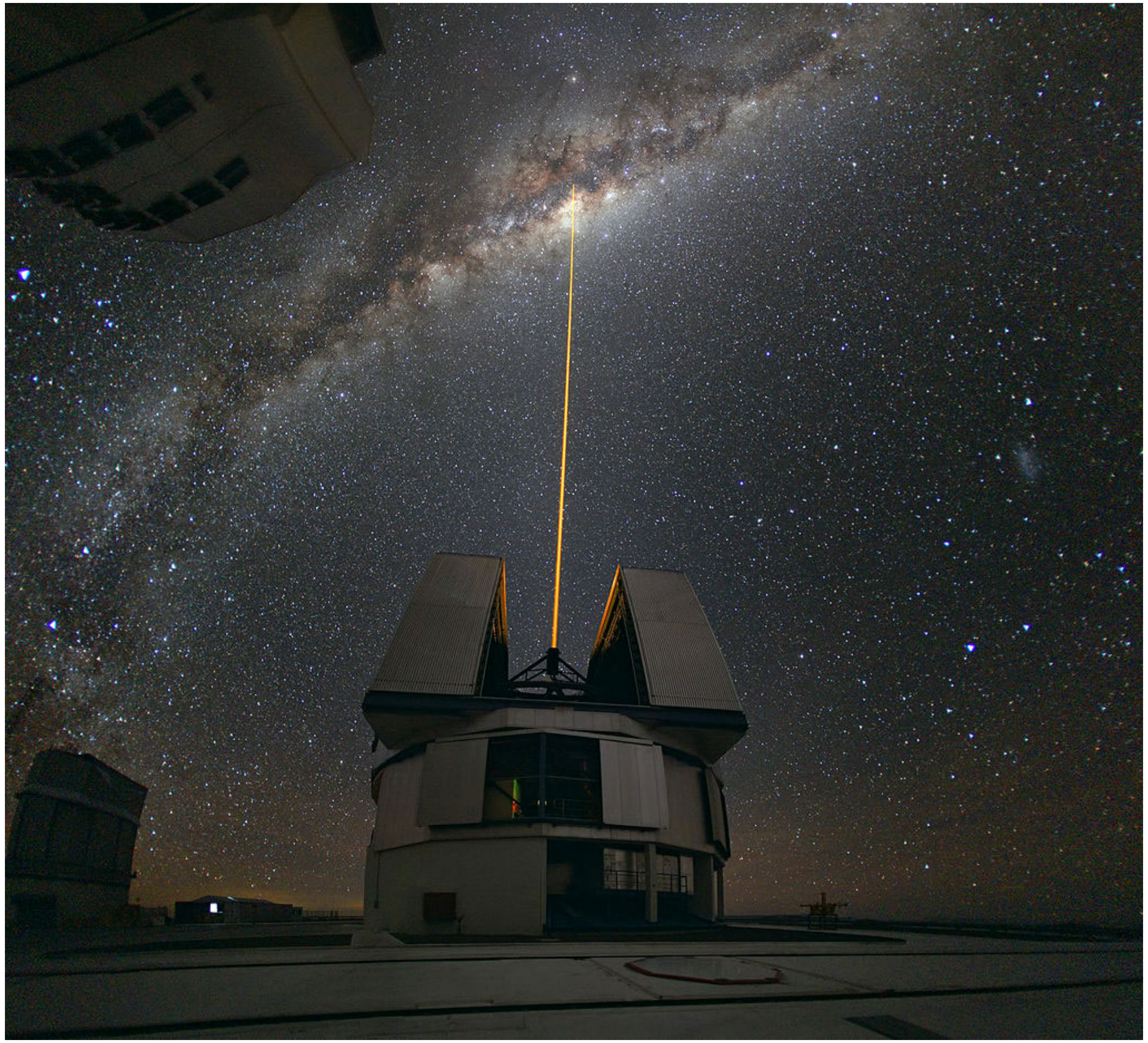
RCWS Options Considered:

- Fundamentally, need to solve a Poisson equation

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

- Many different ways to do so mathematically, and difficult to model which methods provide the best performance
- Survey of literature shows two main classes for algorithms
    - FFT Method
    - Zernike Matrix

2 - Evidence of Baseline Feasibility



Outline

- Cover key critical project elements (CPEs)
- First level feasibility analysis of key CPEs

- Organized by system function
  - Image source
  - Optical system
  - Shack-Hartmann Array
  - Roddier Curvature Wavefront Sensor
  - Testbed
  - Environmental Sensing System
  - Algorithm and Software

2.1.1 Image Source CPEs

Key CPEs:

- Image source must effectively appear as a point source.
- Image source must be able to scale intensity down to 1/128th maximum intensity.
- Image source output intensity must remain stable over the duration of data capture.

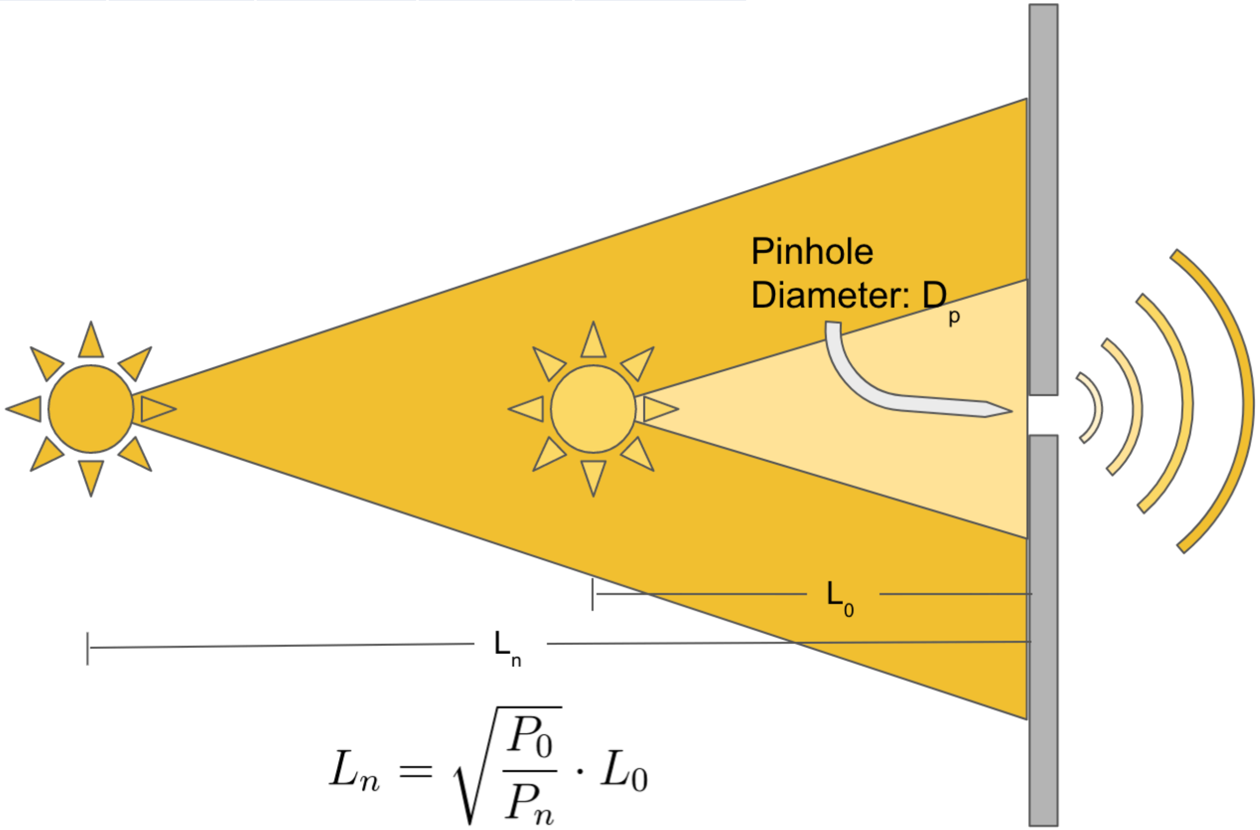
2.2.1 Image Source Feasibility

Power Ratio (Po/Po0)	1	1/2	1/4	1/8	1/16	1/32	1/64	1/128
Length Ratio (Ln/L0)	1.00	1.41	2.00	2.83	4.00	5.66	8.00	11.32

$$P = \int I \cdot \mathbf{dA}$$

$$P_{out} = P_{source} \frac{A_{pinhole}}{L^2 \Omega_{source}}$$

$\Omega =$ Solid angle subtended radiation

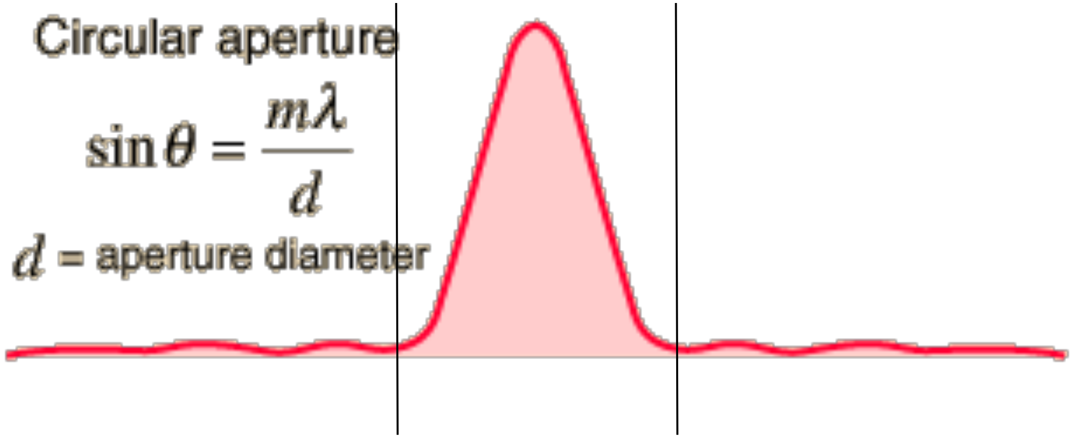


$$L_n = \sqrt{\frac{P_0}{P_n}} \cdot L_0$$

Image Source Feasibility

- 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 450nm wavelength can be at most about 13 µm
  - Worst case value using blue light (smallest wavelength)
  - Standard 10 µm pinhole works, and is available

Circular Aperture Diffraction Pattern



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

Image Source Feasibility

$$I_e = P/\Omega$$

$$\Omega_{pinhole} = 2\pi \left[1 - cos\left(arctan\left(\frac{r_{pinhole}}{l}\right)\right)\right]$$

$$P_{out} = I_e * \Omega_{pinhole}$$

Where l is distance from emitter to pinhole

Pinhole Size Requirements:
- 13 microns maximum
- 10 micron pinhole available for $70

Power requirements of source to satisfy system signal-to-noise ratio requirement:
- 125 W
- Could be much lower if emitter has a narrower viewing angle (assumed a hemisphere of light output)

Intensity Variation:
- Varying intensity by moving emitter is simple to calculate and removes issues associated with low-output emitter instabilities
- Required intensity range can be achieved with throw from 1mm to 11.3mm

Need to determine acceptable change in intensity over duration of data capture

2.1.2 Optical System CPEs

Key CPEs

- The optical system must introduce one or more useful combinations of Zernike modes.
- The sensitivity of mechanical adjustments at the expected Strehl ratio must be determined and should be in range for the actuators accuracy,
- Optical system random error must be below Δ1/100 in Strehl ratio

2.2.2 Optical System Feasibility (Selection of Mirror for Aberration Control)

Introduction of aberrations:

- Using the model of the optical system, Zemax used to calculate small tilts
- Tips and Tilts for Mirror M1
  - Tilt about X: 0.1 deg gives a Strehl ratio of 0.586
  - Tilt about Y: 0.1 deg gives a Strehl ratio of 0.833

- Tips and Tilts for Mirror M2
  - Tilt about X: 0.1 deg gives a Strehl ratio of 0.945
  - Tilt about Y: 0.1 deg gives a Strehl ratio of 0.978

- Mirror M2 is less sensitive to adjustment, thus is more favorable for these tight tolerances and is well within the specifications

2.2.3 Optical System Feasibility (Selection of Axes)

- **Introduction of aberrations:**
  - Using the model of the optical system, Zemax used to calculate small tilts
  - Tips and Tilts for Mirror M2
    - Tilt about X: 0.06° gives a Strehl ratio of 0.978 (1/50)
      - And 0.135° gives a Strehl ratio of 0.9
    - Tilt about Y: 0.216° gives Strehl ratio of 0.9
      - And 0.098° gives a Strehl ratio of 0.978(1/50)
  - Tilt about X is favorable as it starts at a lower angle meeting our control's specification and is well within the specifications
  - From Zemax Simulation the optical system Error Strehl Ratio = 1.00 giving us zero random Strehl's Ratio : High quality Mirrors

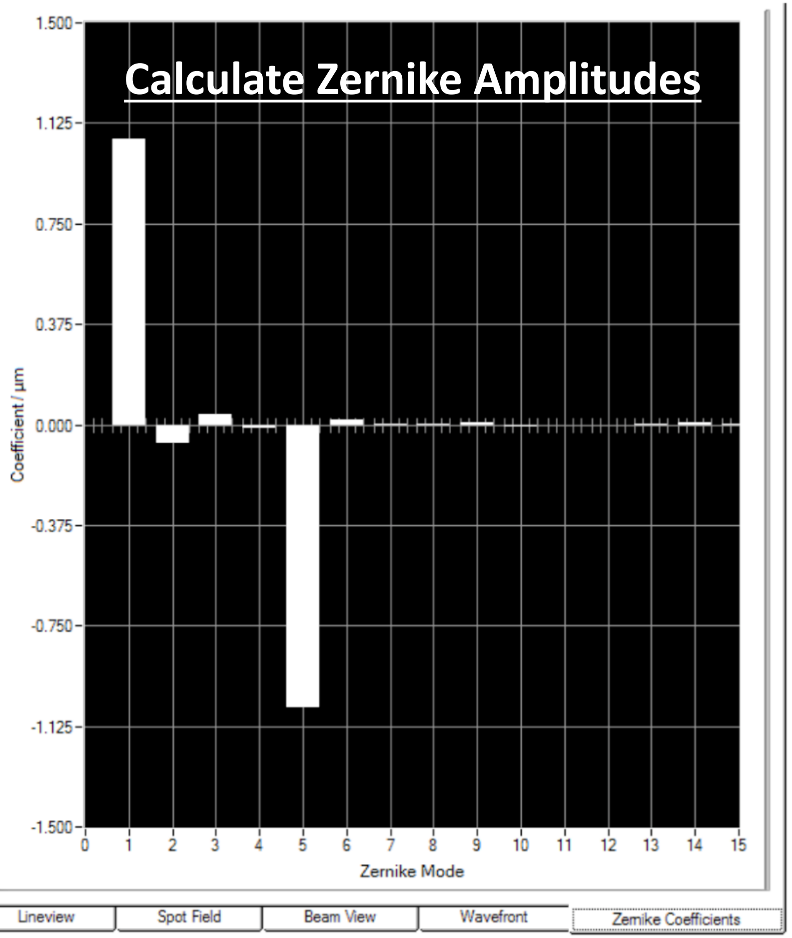
2.1.3 Shack-Hartmann Array CPEs

Key CPEs

- Additional resources required to operate the SHA must be determined.
  - Determine what processing is done by the included software.
  - Determine how the SHA interfaces with the computer.

2.2.3 Shack-Hartmann Array Feasibility

- ThorLabs WFS150-7AR is provided by the customer.
- Sensor package measures wavefront curvature.
- ThorLabs-provided software calculates Zernike Amplitudes
  from wavefront measurements.
- The sensor interfaces with a computer over USB.



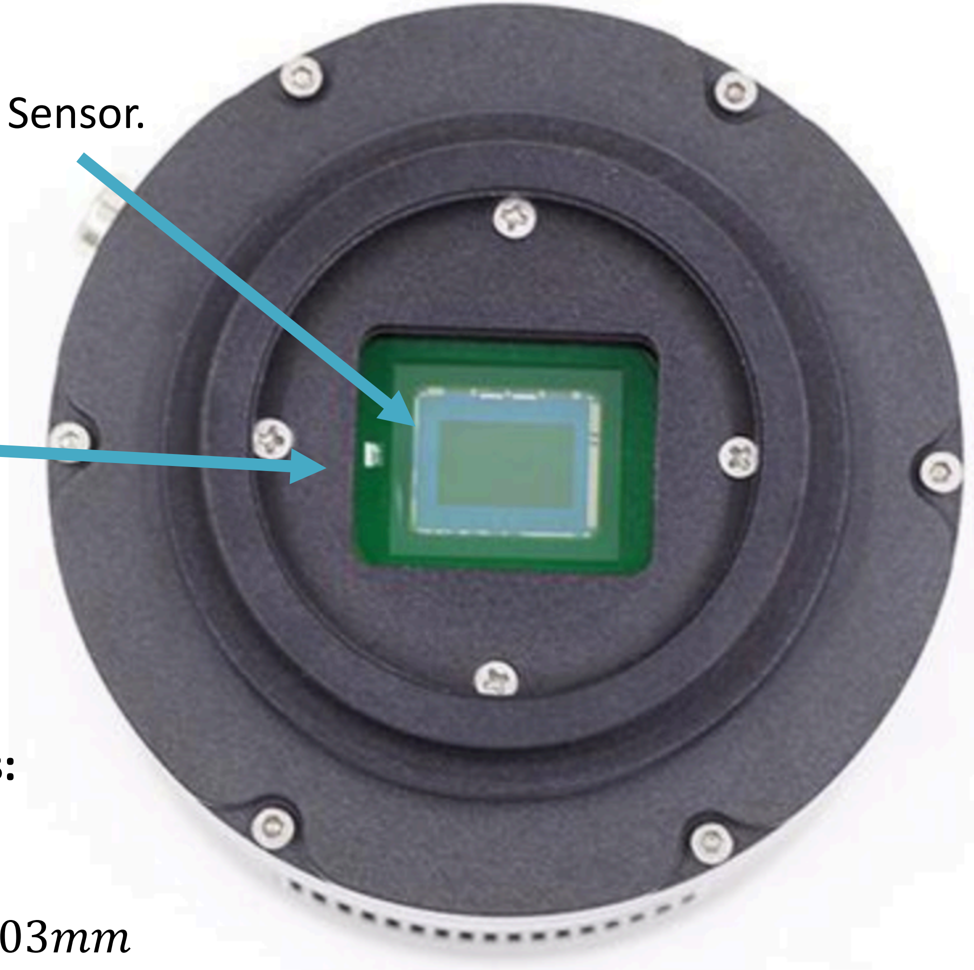
Images from ThorLabs WFS manual [2].

2.1.4 Roddier Curvature Wavefront Sensor CPEs

QHY174M from QHYCCD [8].

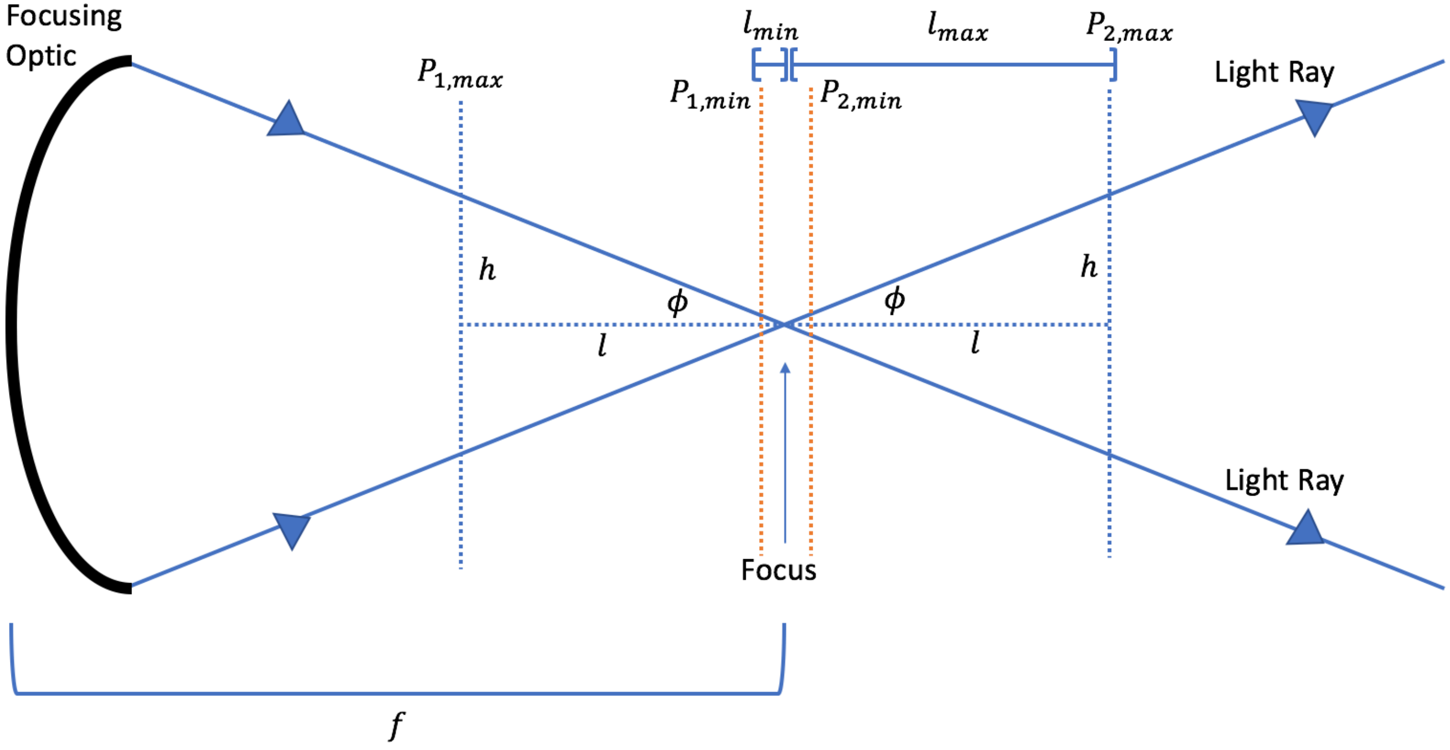
Key CPEs

- The optimal amount of defocus to use must be determined.



CMOS Sensor Characteristics:
Effective Pixels: 1920×1200
Pixel Size: $5.86\mu m \times 5.86\mu m$
Effective Area: $11.25mm \times 7.03mm$

2.2.4 Roddier Curvature Wavefront Sensor Feasibility



Defining Maximum Translation Distance of RCWS:

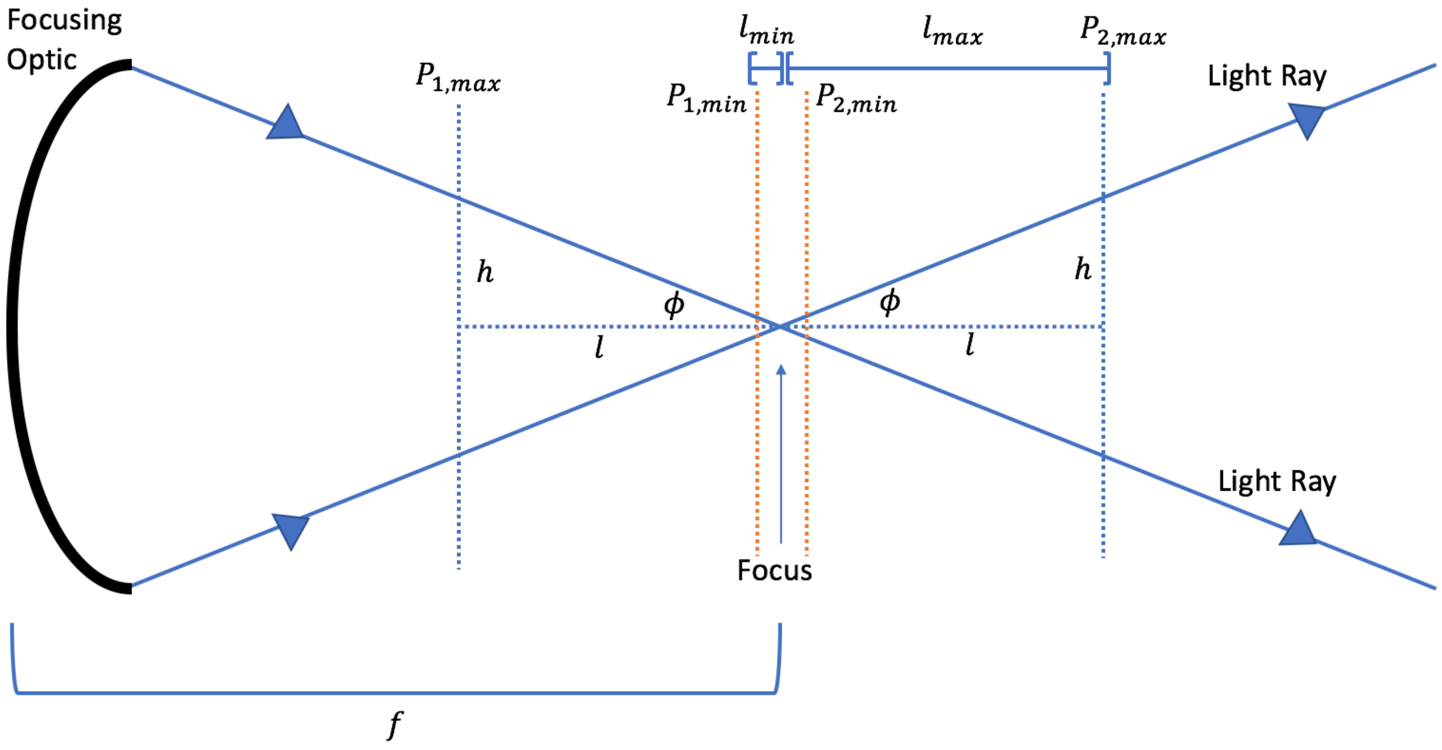
- This is done geometrically using the physical dimensions of the QHY174M.

$$l_{max} = \frac{h_{max}}{\tan(\phi)}$$

$$l_{max} = \frac{3.515[mm]}{\tan(3.286°)}$$

$$l_{max} = 61.22[mm]$$

Roddier Curvature Wavefront Sensor Feasibility



Defining Minimum Translation Distance of RCWS:

- In order to get 11 different Zernike Amplitudes, it requires at least 11 different Intensity values.
  - This is true because Zernike Polynomials are orthogonal.
- Intensity is measured discretely on the pixel level, so we require ≥ 11 pixels.
  - This can be determined using the physical dimensions of the utilized CMOS.

$$l_{min} = \frac{h_{min}}{\tan(\phi)}$$

$$l_{min} = \frac{11.72[\mu m]}{\tan(3.286°)}$$

$$l_{min} = 204.13[\mu m]$$

2.1.5 Testbed CPEs

Key CPEs

- Optical components must be mounted to reduce random error.
- Degrees of freedom controlled with enough precision.
- Experiment sufficiently isolated from external light, vibration, and temperature fluctuations.

2.2.5 Testbed Feasibility

Traverses

- Both the manual and motorized traverses will provide the adjustment ranges and resolutions that are required for testing.
- Both traverses are designed to be easily mounted to an optical breadboard.

Mirror Mounts

- The mirror mounts that will be manufactured by the team will constrain all rigid body motion for each mirror.
- The mounts will also allow for adjustment of the angular position of the mirrors to ensure proper alignment.
- The mirror mounts do not wrap around the sides of the mirrors to prevent them from blocking the image.
- The mirror mounts will be powder coated matte black to prevent light contamination from reflections off of the mounts.

Alignment of Optical Elements

- Using the stages and mounts for each element of the optical system, they will be able to be accurately positioned on an optical breadboard for testing

2.1.6 Environmental Sensors CPEs

Key CPEs

- Sensors must have resolution to identify errors outside of the limits of the experiment.
- Data capture system must be able to process all data generated during a capture cycle.
- Sensors must not interfere with the operation of the rest of the system.

Images from High Point [9] and Digikey [10]

2.2.6 Environmental Sensor Feasibility

Mounting

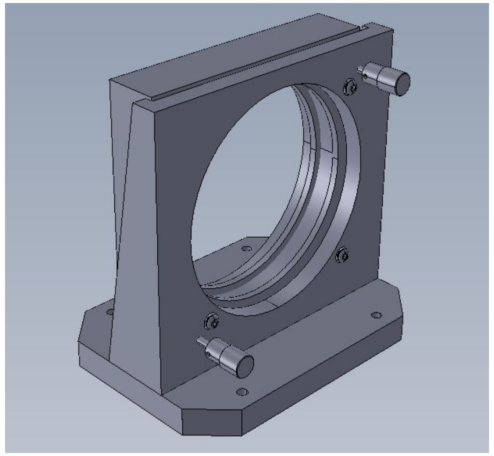
- Mirror backsides will be exposed and should not interfere with light path. Surface mounting may be possible.
- Mounting on backsides of RCWS image sensor and SHA image sensor.

Environmental Stability

- Currently, requirement is only to *monitor* environmental changes.

Microcontroller and Sensors:

- ADXL344 Digital Output Accelerometer may transfer data at up to 3200 Hz
- AD592CNZ-ND Temperature sensor is capable of ±0.5°C accuracy at up to ±0.01°C resolution
- From 12 total sensors at a sampling rate of about 1kHz, data transfer requirements were found as follows:
  - Temperature sensors transfer over I2C. 6 temp sensors * 11bits * 1000Hz = 66 kbps.
  - Accelerometers may transfer over SPI or I2C. 6 accel * 13bits * 3 directions * 1000Hz = 234 kbps = 29 kBps
- Date rate for SPI must run at about 351khz. I2C must run at around 100kbps.
  - A typical Arduino can run SPI at many times this speed and I2C at a few times this speed.
  - Flash write speeds may be inconsistent, but microcontrollers such as the ATSAME70J19 (which has 256kB SRAM and 512 kB Flash) should provide enough memory buffer (more memory is available for other microcontrollers)

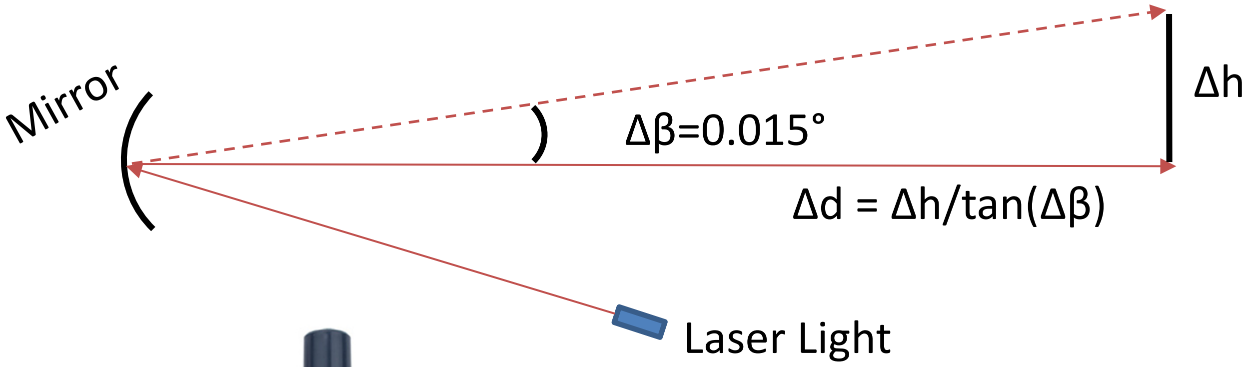


Images from [1], [8]

2.2.6 Environmental Sensors Cont.

Alternative / Addition to Accelerometers

- *Laser Movement Amplifier*
  - Use an image detector for increased resolution
  - Good for use of rotational movement
  - Hard to adapt for translational movement
  - Mount a flat mirror on elements of interest
    - Displacement of laser spot indicates rotational movement
    - Necessary lever arm depends on resolution of displacement measurement. For example, for a Δh resolution of 0.5 cm the required arm is 17.1 meters.
- *Dial Gauge Indicator*
  - Suitable for both rotational and translational measurement
  - Micrometer resolution models available



2.1.7 Algorithm and Software CPEs

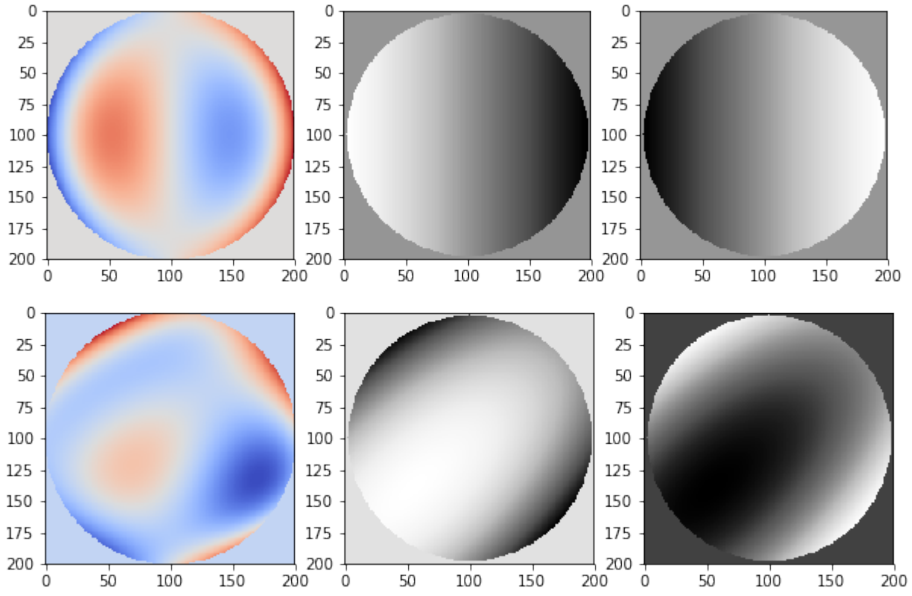
Key CPEs

- Algorithm must be validated without using the RCWS hardware
- Two methods will be implemented to help validate results.
- Software should automate the experiment to improve quality of data collected.

2.2.7 Algorithm and Software Feasibility

Validate captured images:

Generate ZPC in Zemax → Create Simulated Images → Compare results



Validate computed Zernike amplitudes:

Model test in Zemax → Run RCWS software → Compare Zernike amplitudes

```
Listing of Zernike Standard Coefficient Data

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)
```

3.1 Feasible CPEs

Testbed
- Mirror mounts manufacturable
- Stages provide necessary resolution
- Optical path fits on 2 x 4 foot table

Image Source
- Point source achieved with appropriate pinhole, change intensity level by displacement

Optical System
- DOFs introduce required aberrations
- Resolution of adjustment is achievable

Shack-Hartmann Array
- Works out of the box
- USB interface to computer

Roddier Curvature Wavefront Sensor
- Max/Min defocus identified
- USB interface detector to computer

Algorithm
- Algorithm validated with Zemax
- Images can be validated by simulation

Environmental Sensors
- Mirror mounting possible,
- Generic sensors provide needed accuracy/precision

3.2 Studies Still Needed

Testbed

- Manufacture or purchase optical bench
- Find a suitable test/storage location
- Determine need to move sensors to follow beam

Image Source

- Identify acceptable variation in intensity
- Quantify effects of "pinhole camera" effect

Optical System

- Identify exact locations for beamsplitter and wavefront sensors.

Shack-Hartmann Array

- Further understand ThorLabs-provided software.

Roddier Curvature Wavefront Sensor

- Identify necessary resolution of movement.

Algorithm

- Proof of concept

Environmental Sensors

- Could the reflection measurement method still be feasible?
- Testing of real-world hardware transfer rates

3.3 Strategies for Moving Forward

Testbed
- Manufacture or purchase optical bench.
- Find a suitable test/storage location.
- Determine need to move sensors to follow beam.

Image Source
- Identify acceptable variation in intensity.
- Quantify effects of "pinhole camera" effect.

Optical System
- Implement algorithm to determine sensitivities of the system.

Shack-Hartmann Array
- Verify output results of provided software with synthetic model.

Roddier Curvature Wavefront Sensor
- Use synthetic model the define optimal translational distance and resolution.

Algorithm
- Implement the solution to the transport of intensity equation.

Environmental Sensors
- Real world testing of sensor performance by building a prototype.
- Explore lately-considered alternatives.

3.4 Budget

- Using quality components and motorized stages **reduces** error introduction, therefore improving data quality
- Applied for ***Engineering Excellence Fund***
- Project is supported by ***NASA Glenn Research Center*** through the *APRA* program. Additional funding on scale of $5k - $10k is covered

Description	Cost Each	Quantity	Total
Edmund Optics 32-069-522 Parabolic Mirror	$600.00	2	$1,200.00
10 um Pinhole	$47.00	1	$47.00
Pellicle Beamsplitter	$160.00	1	$160.00
Motorized Linear Traverse	$824.00	1	$824.00
Motorized Pitch/Yaw Platform	$2,072.00	1	$2,072.00
Motor Controllers for Stages	$626.00	3	$1,878.00
Powersuppy and USB connection for 3 controllers	$485.00	1	$485.00
Power supply for source	$538.95	1	$538.95
Lux Meter (Extech 407026)	$200.00	1	$200.00
L520P50 520nm Laser Diode	$64.50	1	$64.50
Vibration Damping Leveling Feet	$20.65	4	$82.60
24"x48"x0.5" Optics Breadboard	$913.00	1	$913.00
4" Steel Tube for Optics Frame	$325.00	1	$325.00
Aluminum plate stock to manufacture mounts	$500.00	1	$500.00
Temperature Sensors	$21.33	6	$127.98
Accelerometers	$3.39	6	$20.34
Powder coating material	$13.44	1	$13.44
ThorLabs WFS150-7AR Shack-Hartmann Sensor	$4,009.00	1	$4,009.00
ASI120mm-S	$249.00	1	$249.00
QHY174M/C cooled CMOS sensor	$939.00	1	$939.00
Projects Budget			-$5,000.00
Provided Equipment and Sensors			-$5,197.00

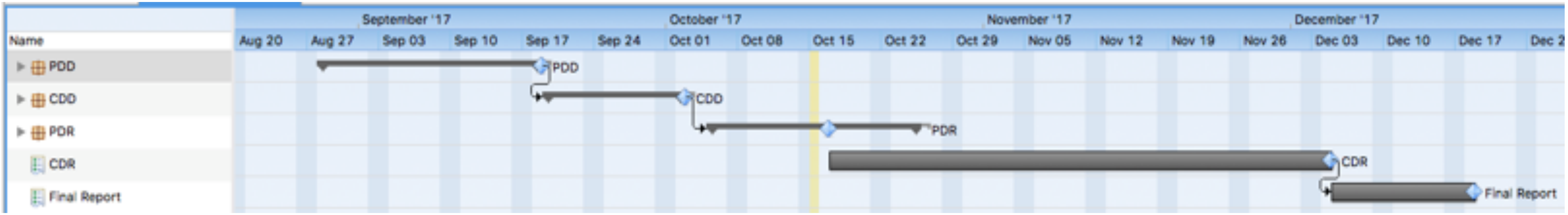
Total Cost	$14,648.81
Secured Funding	-$10,197.00
Additional Required	$4,451.81
Min. Additional Funding	$5,000
Remaining	$548

Secured Items

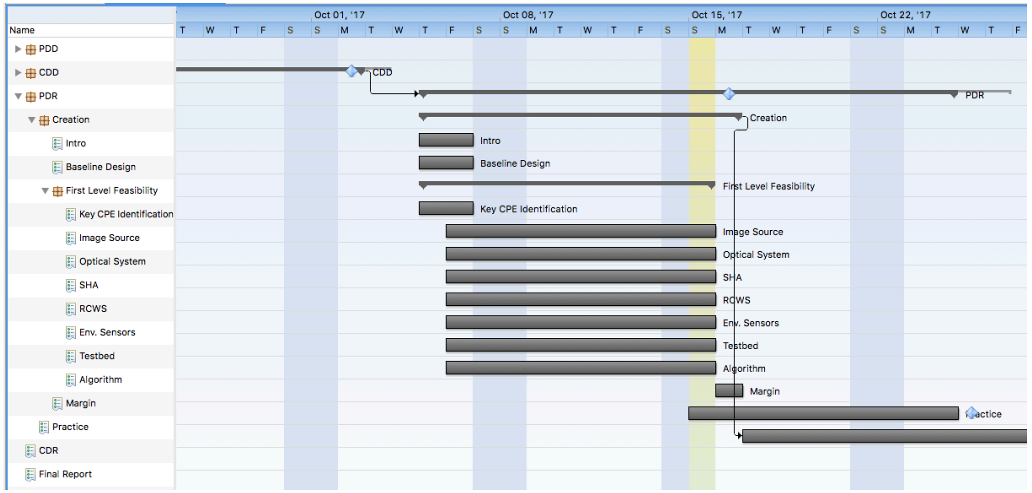
Unacquired Customer Funding

3.5 Schedule

CDR to Final Report



PDR (Complete)



Summary

- PDR is complete
- CDR planning has begun
    - Primary focus areas will fall under the seven main subsystems

Questions?

Thanks to Eliot Young, Bob Woodruff, and Dr. Sternovsky

References

[1] Weisstein, Eric W. "Zernike Polynomial." From *MathWorld*--A Wolfram Web Resource. http://mathworld.wolfram.com/ZernikePolynomial.html

[2] "WFS Series Operation Manual." *Optical Wavefront Sensors (Shack-Hartmann)*, 23 Oct. 2015, www.thorlabs.com/drawings/c0b25c9fdcbf0d78-4CEA4665-0502-3F86-B4B8B99A1871D293/WFS150-7AR-Manual.pdf.

[3] "ADXL344 Data Sheet." Analog Devices. 23 Feb. 2017 http://www.analog.com/media/en/technical-documentation/data-sheets/ADXL344.pdf

[4] "DS18B20 Data Sheet." Maxim Integrated. Jan. 2015 https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf

[5] "Serial Peripheral Interface (SPI)." *Spark Fun*, Https://Learn.sparkfun.com/Tutorials/Serial-Peripheral-Interface-Spi, learn.sparkfun.com/tutorials/serial-peripheral-interface-spi.

[6] "Circular Aperture Diffraction." HyperPhysics, http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/cirapp2.html

[7] "Speed." *I2C Bus*, www.i2c-bus.org/speed/.

[8] "QHY174M/C," QHYCCD, QHYCCD, http://www.qhyccd.com/QHY174.html.

[9] "EVAL-ADXL344Z-S." *Analog Devices Inc. | Development Boards, Kits, Programmers | DigiKey*, www.digikey.com/product-detail/en/analog-devices-inc/EVAL-ADXL344Z-S/EVAL-ADXL344Z-S-ND/3542793.

[10] "6.00" Diameter, Optical Mount Medium | Edmund Optics." *Edmund Optics Worldwide*, www.edmundoptics.com/optomechanics/optical-mounts/optical-mirror-mounts/6.00quot-diameter-optical-mount-medium/.

BACKUP SLIDES

PDR Outline

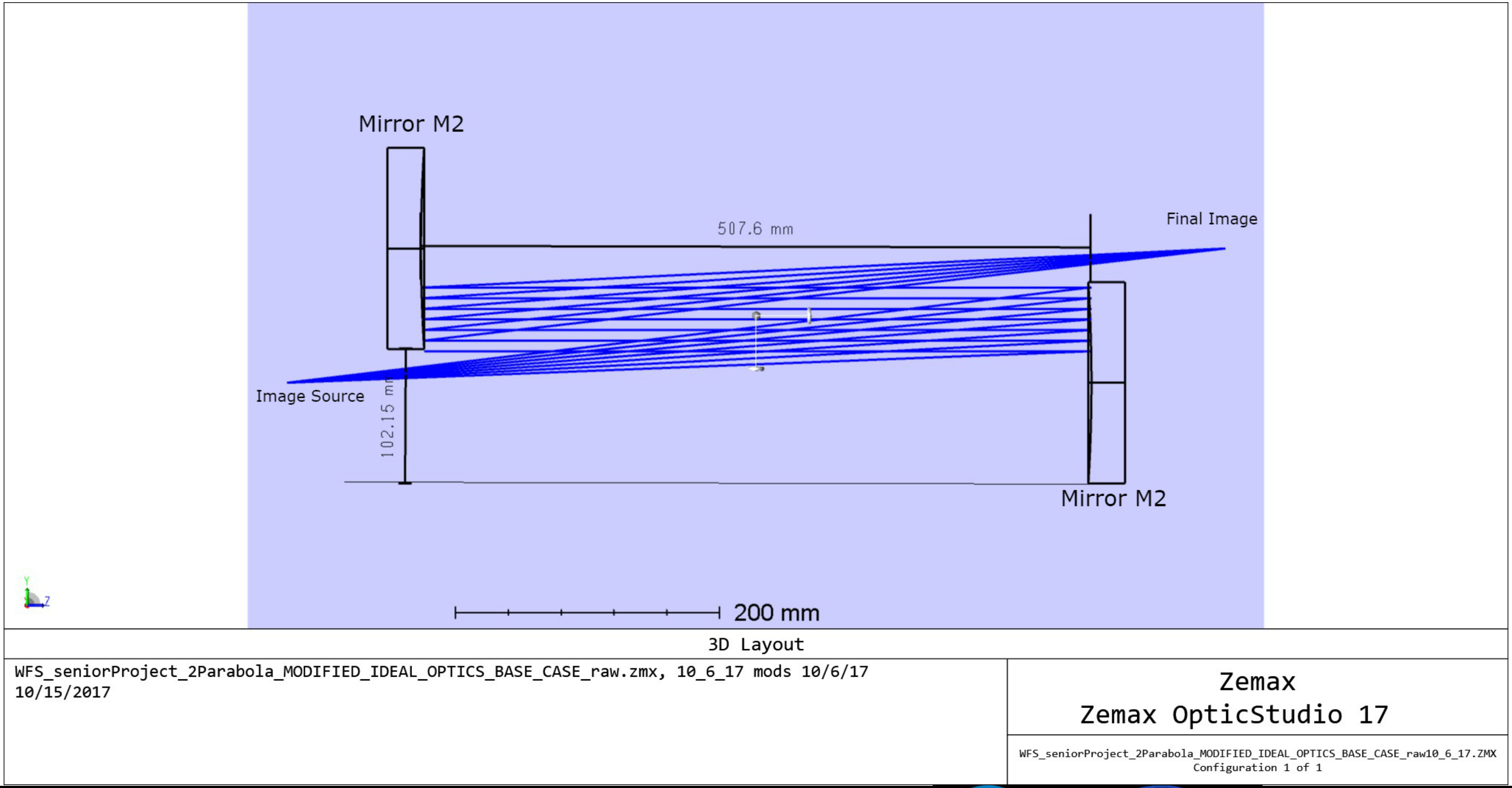
- Introduction
  - Project Brief
    - Objectives
    - CONOPS
    - FBD
    - Requirements
  - Baseline Design
    - Image Source
    - Optical System
    - SHA
    - RCWS
    - Testbed
    - Environmental Sensors
    - Algorithm and Software
- Evidence of Baseline Feasibility
    - Image Source
    - Optical System
    - SHA
    - RCWS
    - Testbed
    - Environmental Sensors
    - Algorithm and Software
- Status Summary
  - Feasible CPEs
  - Studies Still Needed
  - Strategies Moving Forward
  - Budget
  - Schedule

Backup Links

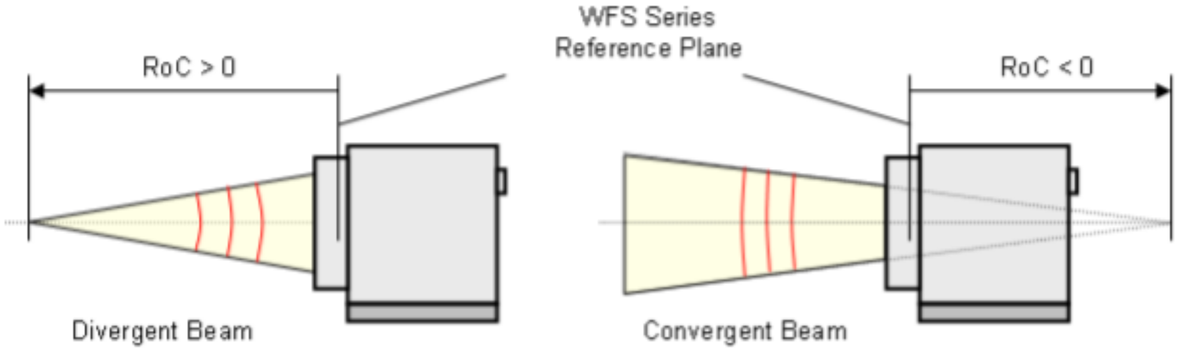
- Optical Model
- SHA
- RCWS
- Budget
- Algorithm
- Requirements
- Environmental
- Trade Studies

- Evidence of Baseline Feasibility
  - Image Source
  - Optical System
  - SHA
  - RCWS
  - Testbed
  - Environmental Sensors
  - Algorithm and Software
- Status Summary
  - Feasible CPEs
  - Studies Still Needed
  - Strategies Moving Forward
  - Budget
  - Schedule

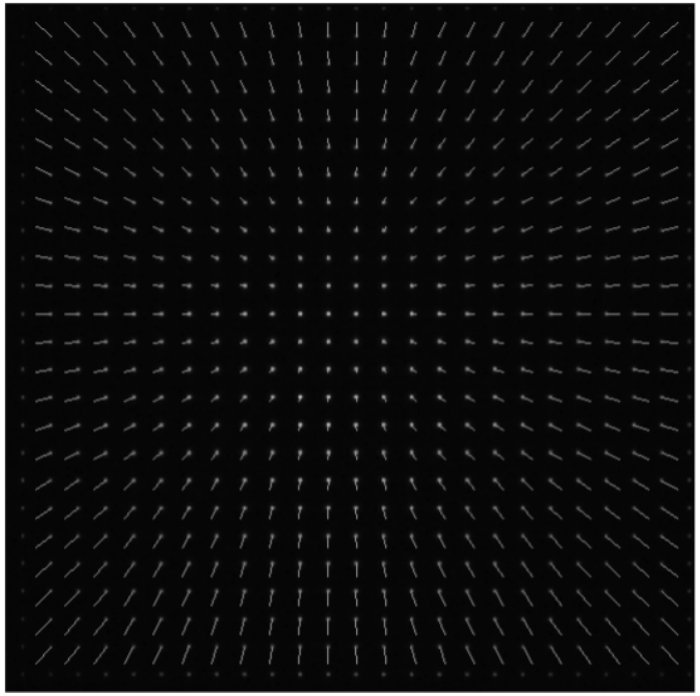
Appendix: Optical Model Backup Slide



Appendix: Shack-Hartmann Array Feasibility



(Left) ThorLabs definition for Radius of Curvature (RoC). Used towards a post-processing correction for the SHA if placed in a non-collimated beam. This model is capable of these corrections where others may not be. (Below) Example of a spotfield from the SHA for a convergent beam. Images taken from ThorLabs WFS150-7AR manual[2].



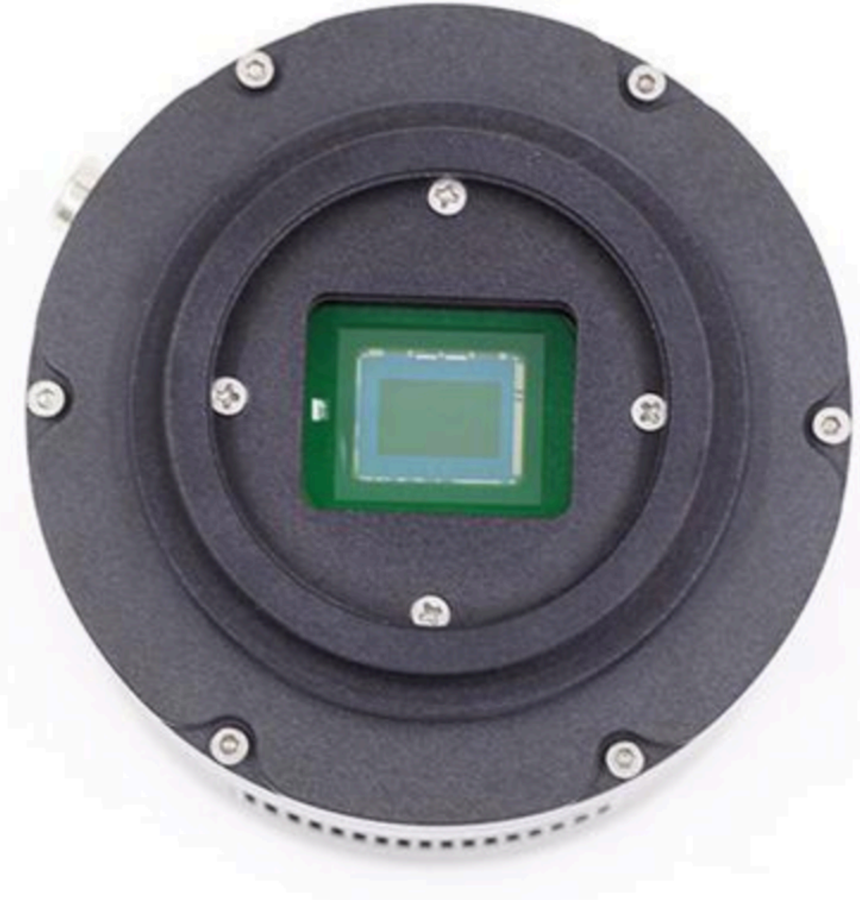
Discussion of using collimating optic versus measuring the divergent beam.

- Using a collimating optic before the SHA doesn't require knowledge of the radius of curvature of the incoming light.
- By placing the SHA in non-collimated light, the RoC is then required. This configuration is sufficient for this project, as the RoC can be determined from the forward-predictive model.

Appendix: RCWS Additional Information

Why are there no off-the-shelf RCWS solutions?

- It is necessary for us to create our own RCWS sensing system, as there are no commercially available RCWS sensors.
- This is due to the benefits of the RCWS; there is no need to carry a stand-alone wavefront error sensor.
    - Nearly every optical system will have a method for adjusting the focus, and therefore, the ability to measure the wavefront aberrations using only the on-board optics with the Roddier method.



Appendix: Roddier Curvature Wavefront Sensor Feasibility

Why is there only an upper and lower bound? Where is the optimal distance? What is the required resolution of the image sensor?

- For baseline feasibility of the project, it was deemed sufficient to provide upper and lower boundaries on the optimal amount of defocus.
  - In truth, <u>the optimal location will be derived from the synthetic model created of the optical system</u>.
    - The minimum value would correspond to a distance where the higher order Zernike Amplitudes can still be distinguished.
  - This optical model is currently being developed, but the functionality is not mature enough to assist with this optimal distance determination.
- The <u>required resolution of the translational stage will also be determined by the synthetic model</u>, but this is still being developed.
- **These questions have not yet been answered, but are acknowledged as CPEs.**

Appendix: 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:

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

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

$$Uncertainty = 0.735\%$$

Appendix: Budget Feasibility if Additional Funding Not Obtained

- The motorized stages would be replaced with comparable manual stages
- The optical breadboard area would be minimized
- The table would be built shorter
- Less budget for stock materials to build mounts
- Margin of $112.51 is too small for currently unknown expenses (including shipping costs)

Description	Cost Each	Quantity	Total
Edmund Optics 32-069-522 Parabolic Mirror	$600.00	2	$1,200.00
10 um Pinhole	$47.00	1	$47.00
Pellicle Beamsplitter	$160.00	1	$160.00
Manual Linear Traverse	$403.00	1	$403.00
Manual Pitch/Yaw Platform	$888.00	1	$888.00
Power supply for source	$538.95	1	$538.95
Lux Meter (Extech 407026)	$200.00	1	$200.00
L520P50 520nm Laser Diode	$64.50	1	$64.50
18"x36"x0.5" Optics Breadboard	$558.00	1	$558.00
Vibration Damping Leveling Feet	$20.65	4	$82.60
Steel Tube for Optics Frame	$150.00	1	$150.00
Aluminum plate stock to manufacture mounts	$300.00	1	$300.00
Temperature Sensors	$7.00	6	$42.00
Accelerometers	$40.00	6	$240.00
Powder coating material	$13.44	1	$13.44
ThorLabs WFS150-7AR Shack-Hartmann Sensor	$4,009.00	1	$4,009.00
ASI120mm-S	$249.00	1	$249.00
QHY174M/C cooled CMOS sensor	$939.00	1	$939.00
Projects Budget			-$5,000.00
Provided Equipment and Sensors			-$5,197.00

Total Cost	$10,084.49
Secured Funding	-$10,197.00
Remaining	$112.51

Secured Items

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)

Appendix: 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

Appendix: Accounting for "spot shifts" and wavefront distortion on the sensor location

As shown in the Shack-Hartmann Array Feasibility slide, the wavefront imagery can stray. For the optimal distance for sensor location, tolerances need to be taken into account. Maximum area coverage on the sensor provides the greatest FFT performance. But shifts can stray off of the sensors with wavefront distortion. This has yet to be studied but is acknowledged.

Appendix: Requirements Flow Down

Use a controlled source to feed the system a known image over a range of intensities.

FR.1 The image source shall be designed to appear as a point source emitter.

Both the RCWS and the SHA are designed to operate with a point source image. In most telescopes the incoming rays can be assumed to be parallel but in the restricted space of the testbed that assumption does not hold. The optical design delivered by the customer requires a point source at the focal point of the first mirror to recreate the conditions seen by a telescope observing a distant star

FR.1 The image source intensity shall vary over one octave.

Intensities over one octave represents the difference between the four brightest stars and the 4800 brightest stars in the night sky. A sensor capable of using a dim source to calibrate is highly valuable because it requires to be repositioned less during a mission.

Appendix: Requirements Flow Down

Introduce known errors to the wavefront before it reaches either sensor.

FR.2 The optical system shall image a point source at both the RCWS and SHA sensors.

As both sensors require a point source image for best results this requirement is given.

FR.2 The optical system shall use two Edmund 32-522 parabolic mirrors to collimate and refocus the image at the sensors.

Stipulated by the optical design given by the customer.

FR.2 Wavefront error shall be introduced quantitatively by at least one mechanical degree of freedom.

Other methods to introduce wavefront error such as a deformable mirror exist but are beyond the needs of this project. Moving the optical system in any one degree of freedom is unlikely to produce pure responses in single Zernike modes but this is of little concern to the project. It is more important that the measured results agree with the simulated results.

Appendix: Requirements Flow Down

Introduce known errors to the wavefront before it reaches either sensor.

FR.2 Wavefront error shall be introduced in steps no larger than those corresponding to a 1/50 expected change in Strehl ratio.

The utility of wavefront sensors aboard real missions is usually to feed an adaptive optical system to correct for errors. Finer resolution translates to superior mission performance. The ability to measure the parameter in detail is imperative for the project.

FR.2 Total wavefront error introduction must be great enough to reduce the simulated Strehl ratio by 1/10.

This requirement is chosen to specify possible characterizations over a wide range of total wavefront error.

A wavefront error sensor that only works with little to no error is clearly less desirable than another without that quality.

FR.2 Random error introduced during data capture shall not exceed that corresponding to an expected reduction in Strehl ratio by 1/100.

This requirement stems from the expectation to measure 1/50 changes in Strehl ratio. If any more than half that is introduced in an uncontrolled manner it casts doubt onto the desired measurements.

Appendix: Requirements Flow Down

Measure wavefront error using an off the shelf Shack Hartmann Array.

FR.3 The Shack Hartmann Array used shall be Thorlabs model WFS150-7AR, provided by the customer.

As this sensor costs nearly as much as the budget for the project there is no choice involved.

FR.3 The SHA shall be placed at the appropriate pupil of a collimated beam of the image.

The SHA does not include the required hardware to collimate the beam, and must be located properly so as to detect errors on the mirror surface.

FR.3 The Shack Hartman Array shall compute the wavefront error in terms of Zernike Polynomial Coefficients of wavelengths according to Nolls 1976 definition.

Specified by the customer, this requirement helps unify the wavefront error reporting method.

FR.3 The SHA shall be protected and returned to the customer in the condition in which it was received.

Natural precautions must be taken when handling expensive hardware the belongs to others.

Appendix: Requirements Flow Down

Measure wavefront error using a custom designed Roddier Curvature Wavefront Sensor.

FR.4 A hardware Roddier Curvature Wavefront Sensor shall be developed.

Because the RCWS is a recent development there exist no off-the-shelf solutions, meaning that a sensor shall be developed on the principal of operation alone.

FR.4 The RCWS shall be nominally positioned at the focal point of the optical system, and the sensor plane must move before and aft of the focal plane with fine enough resolution to distinguish a 1/50 change in Strehl ratio.

The principal of operation of the RCWS requires that the focal point move ahead of and behind the sensor plane, but it does not require that that is achieved any one way. The resolution of movement determines in part the resolution of the sensor.

FR.4 ASI120MM-S (monochromatic) and QHY174M/C CMOS sensors shall be supplied by the customer to serve as the detectors for the RCWS.

Again, the costs of these optical components is prohibitive to the project and so there is no option but to use the provided sensors

Appendix: Requirements Flow Down

Measure wavefront error using a custom designed Roddier Curvature Wavefront Sensor.

FR.4 Two algorithms, a Fast Fourier Transform and a Matrix Solution, to determine wavefront error Zernike Polynomial Coefficients from image detector and focal plane displacement data shall be developed and compared. Because this is new technology there exist several valid strategies for processing the raw data. To effectively evaluate the RCWS the two most prominent methods will be employed.

FR.4 The RCWS shall be capable of determining Zernike Polynomial Coefficients 2-11 by the Noll 1976 definition. Again, the Noll definition of ZPCs provides a uniform reference to which both sensors can be compared.

Appendix: Requirements Flow Down

Compare the response rate of measured to induced wavefront error for either sensor.

FR.5 The rate of change of measured wavefront error with respect to mechanical deviation shall be the primary metric of the sensor characterization.

This method of comparison drastically reduces the required tolerances in manufacture and assembly of the testbed.

FR.5 The comparison between wavefront sensors shall be made down to the level of wavefront error that results in a one hundredth (1/100) reduction in Strehl ratio.

Because the utility of the wavefront error sensors is expected to be 1/50 it is only necessary to compare to double that resolution.

Appendix: Requirements Flow Down

Minimize random error introduction and maximize positioning resolution during data captures.

FR.6 The frequency of vibrations present on the main optical components shall be determined up to 300 Hz during a data collection period.

This requirement was specified by the customer in order to help validate data captures.

FR.6 Temperature data local to the six primary optical elements shall be measured to 0.15 degrees kelvin precision and 0.5 degrees K accuracy.

This requirement determined as the temperature change required at the average coefficient of thermal expansion of aluminum over the distance of 1 meter to produce an error corresponding to a 1/100 change in Strehl ratio.

Appendix: Requirements Flow Down

Validate test results with simulation and environmental data logs during exposure.

FR.7 The alignment of optical components must be such that the minimum expected Strehl ratio is at least 0.3.

This requirement chosen at the suggestion of the customer. Based on years of optical experience this is a reasonable value for the Strehl ratio of an optical system on the scale of the provided design.

FR.7 Intentionally introduced deviations shall be measured to precision corresponding to a 1/100 change in expected Strehl ratio.

Again this stems from the need to reliably introduce error on the order of a 1/50 change in Strehl ratio.

FR.7 A method to prevent contamination by external light sources shall be included in the testbed design.

FR.7 The testbed design shall include a method to prevent contamination of the optical components by dust both during testing and while in storage.

Appendix: Environmental Sensors

Customer required that accelerometers be capable of capturing vibrations at frequencies up to 300Hz **(R6.1**). Customer also set hard requirements for the performance of the temperature sensor at an accuracy of ±0.5°C accuracy at up to ±0.15°C resolution **(R6.2)**. And, lastly, the customer also wanted data transfer to be capable at 1kHz **(R6.3)**. No requirements dictate live vs. Post-test processed data or the complete mitigation of detected environmental changes.

Also, I2C data rates were found as: "The speed grades [for I2C] (standard mode: 100 kbit/s, full speed: 400 kbit/s, fast mode: 1 mbit/s, high speed: 3,2 Mbit/s) are maximum ratings. Compliant hardware guaranties that it can handle transmission speed up to the maximum clock rate specified by the mode." [7]

Whereas, typical SPI data rates are described for a baseline Arduino as follows "SPI can operate at extremely high speeds (millions of bytes per second)...you can adjust the data rate. In the Arduino SPI library, the speed is set by the setClockDivider() function, which divides the master clock (16MHz on most Arduinos) down to a frequency between 8MHz (/2) and 125kHz (/128)" [5]

Appendix: Emitter Trade Study

		Incandescent	Halogen	LED	Laser
Metric	Weight	Score	Score	Score	Score
Cost	20%	4	4	4	1
Max Light Output	30%	3	4	2	1
Broadband or SW	50%	1	1	1	4
Weighted Total		2.2	2.5	1.9	2.5

Appendix: Post-Emitter Trade Study

		Pinhole	Iris Diaphragm	Pinhole Wheel
Metric	Weight	Score	Score	Score
Cost	50%	3	2	1
Complexity	30%	3	2	1
Light Output Range	20%	1	3	2
Weighted Total		2.6	2.2	1.2

Appendix: Emitter Power Supply Trade Study

		M1739	E3620A	LM317 Circuit	E3631A
Metric	Weight	Score	Score	Score	Score
Noise Level	45%	4.5	2.5	1.5	5
Output Range	15%	3.5	4	4.5	5
Cost	40%	4	4.5	4.5	1
Weighted Total		4.15	3.5	3.2	3.4

Appendix: Lux Meter Trade Study

		ATP LED Meter	ATP 4-in-1 Meter	Extech 407026
Metric	Weight	Score	Score	Score
Resolution	45%	5	3	3
Detectable Range	25%	5	2	4
Cost	30%	3.5	3.5	3.25
Weighted Total		4.6	2.9	3.3

Appendix: Mirror Coating Trade Study

		Enhanced Aluminum	Protected Aluminum	Protected Gold
Metric	Weight	Score	Score	Score
Relevant R_{AVG}	35%	4.75	4.25	4.9
Coverage of Visible Spectrum	45%	4.3	5	0.4
Cost	20%	4.4	5	3.5
Weighted Score		4.5	4.7	2.5

Appendix: RCWS Configuration Trade Study

		(1)	(2)	(3)	(4)
Metric	Weight	Score	Score	Score	Score
Additional Hardware Required	20%	4	5	3	4
Additional Errors Introduced	40%	4.5	3	3.5	4.5
Ease of Operation	10%	4.5	2	4	5
Algorithm Complexity	15%	5	5	5	2
Cost	15%	4	5	4	3
Weighted Total	100%	4.4	3.9	3.75	3.8

1. One Translating Image Sensor
2. One Fixed Image Sensor (Adjusting Optical Focus)
3. Two Fixed Image Sensors with optical beam splitting
4. Two fixed Image Sensors horizontally displaced

Appendix: Environmental Sensors Trade Study

		Thermistors	Thermocouples	Digital IC's
Metric	Weight	Score	Score	Score
Cost	10%	4.5	2.5	4.5
Accuracy	75%	3.5	3.5	4.5
Complexity	15%	4.5	2.5	4.5
Weighted Total		4.2	2.8	4.5

Appendix: Environmental Sensor Mounting Techniques Trade Study

		Mechanical Mount	Double Sided Tape	Hot Glue
Metric	Weight	Score	Score	Score
Sturdiness	75%	4.5	1.5	2
Thermal Conductivity and Vibration Damping	10%	4.5	1	1.5
Adjustability	5%	1	4	3.5
Cost	5%	2	5	5
Time Needed to Implement	5%	2.5	4.5	4.5
Weighted Total		4.1	1.9	2.3

Appendix: Environmental Interface Trade Study

		Commercial Off the Shelf Microcontroller	Custom Built PCB
Metric	Weight	Score	Score
Ease of Use	10%	4.5	2.5
Functionality	80%	3.5	4.5
Cost	10%	4.5	4
Weighted Total		3.7	4.3

Appendix: Mirror Mount Trade Study

		Self-Centering Mount	Optical Mount Medium	Large Angle Mirror Mount	On-Site Option
Metric	Weight	Score	Score	Score	Score
Size	10%	1	3.33	5	4
Weight	5%	5	1.25	4.9	2
Availability	15%	3	5	5	2
Ease of Assembly	40%	5	4	2	4
Cost	30%	2.75	1	4.6	5
Weighted Total		3.6	3	3.7	3.9

Appendix: Linear Traverse Trade Study

		ThorLabs PT1-Z8	ThorLabs LTS-150
Metric	Weight	Score	Score
Movement Precision	20%	5	2.5
Design Limitation	40%	2	5
Cost	40%	3	1
Weighted Total	100%	3	2.9

Appendix: Linear Traverse Trade Study (cont.)

		ThorLabs XYT1	ThorLabs XR25P	ThorLabs PTI-Z8
Metric	Weight	Score	Score	Score
Cost	35%	3.8	5	2.5
Travel Range	20%	2.5	5	5
Resolution	20%	4	4	5
Actuation	25%	2	2	5
Weighted Total		3.03	3.95	4.125

Appendix: Tilt/Tip Platform Trade Study

		ThorLabs TTR001	ThorLabs PY004Z8	ThorLabs PY004
Metric	Weight	Score	Score	Score
Cost	35%	5	2.15	4.6
Travel Range	20%	5	4.5	4.5
Resolution	20%	2.5	5	4
Actuation	25%	2	5	2
Weighted Total		3.81	3.90	3.75