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Apparatus for Wavefront Error Sensor Measurement (AWESoMe)

Optical systems are sensitive to the shape of the wavefront, or the constant-phase surface of electromagnetic radiation, that is received at the detector. Unintentional optical path length variations introduced within the system due to external factors reduce final image quality. In systems that correct for these errors, the heritage Shack-Hartmann Array (SHA) wavefront sensor is the common means of detecting the wavefront shape. A new wavefront-sensing methodology is the curvature wavefront sensing method suggested by F. Roddier [Applide Optics, 1988]. In order for the performance of the two wavefront-sensing methods to be compared in the future, the team created a testbed to control the wavefont conditions, as well as an implementation of the Roddier-method wavefront sensor (RCWS) to compare against the SHA. The test platform was verified to be capable of introducing wavefront error with resolution exceeding $\lambda/50$, vary detector SNR from 100 to 100/128, and automatically perform over 500 tests of unique testing conditions. The RCWS sensor package provides all information required to reconstruct the wavefront and can be operated entirely by software.

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Acronyms

COTS	Commercial Off-the-Shelf
DOFs	Degrees of Freedom
EMR	Electromagnetic Radiation
MCU	Microcontroller Unit
OPD	Optical Path Delay
RCWS	Roddier Curvature Wavefront Sensor
SHA	Shack-Hartmann Array
SNR	Signal to Noise Ratio

Nomenclature

$\Delta t_{sensors}$	Time interval of worst-case sensor scenario
r_{data}	Data rate
w_{temp}	Data size for the temperature sensors
w_{accel}	Data size for the accelerometers
$\#_{dir}$	Number of accelerometer directions
$\#_{sensors}$	Number of sensors

1. Introduction

Electromagnetic radiation (EMR) instruments, including everything from radar telescopes to ultraviolet cameras, are used in scientific missions. One of the most common ranges of EMR is the optical band because it conveys images as they are experienced by individuals. At such short wavelengths even small geometric deformations of the optical path result in a significant reduction in image quality. The quantification of this change in quality is known as wavefront error.

There are a number of ways in which wavefront error can be introduced to an optical system. This includes structural effects such as loading and thermal expansion, as well as atmospheric distortion. In order to correct for these errors, modern optical systems use a wavefront sensor to determine the errors and an actuator to adjust the system.

A wavefront is the continuous constant-phase surface of radiation emitted by a single source. A perfectly focused wavefront is converging and spherical at the detector. Any deviation from such is considered error. The distance to even the nearest star ensures that the incoming wavefront is coherent and effectively planar, so optical systems are designed to transform that planar wavefront into a converging spherical wavefront for the image sensors. This transformation is done geometrically by exploiting the proportional relationship between distance travelled by the light and the phase: $\lambda = \frac{c}{f}$. Here, λ denotes the wavelength of the radiation over which the phase spans a complete period of 2π radians. Therefore, differences in the length equate to differences in the phase and can change the shape of the wavefront.

The current standard method of measuring the wavefront is the Shack-Hartmann Array (SHA). It uses an array of lenslets to focus light onto a CMOS array, and the displacement of the centroid of the light that each individual CMOS sensor detects produces a first-order slope field. The SHA method is not ideal for small payloads because it often requires an additional image detector placed at the pupil of the optical system.

In 1988, and alternate method to wavefront sensing was described by Roddier and Roddier in "Curvature Sensing and Compensation: A New Concept in Adaptive Optics" [1]. Illustrated in Figure 3, this method measures the difference in intensities between two defocused images. These images are taken ahead of and behind the focal plane. These two images are both quantifications of the intensity of light at each point of the image plane, which are then related to the wavefront surface by the Transport of Intensities Equation (TIE). The Roddier Curvature Wavefront Sensing (RCWS) method has the advantage of not requiring any additional equipment or sensors because modern imaging instruments already include a method for adjusting the focal length of the image.

2. Objectives

A body of evidence proving the performance of the Roddier Curvature Wavefront Sensor is required in order to justify its use on future missions. The goal of project AWESoMe is to deliver a system that is capable of recording such a body of evidence. This breaks the objectives of the project into two parts: first to design and build a test platform that supports the required measurements and second to implement a custom-designed RCWS in absence of a commercially-available (COTS) model.

2.1. Test Platform

A test platform will enable collection of performance data to justify the use of an RCWS on future missions. In order to understand the scope, it is important to describe precisely what performance data is of interest. In the case of wavefront sensors the relevant statistics are the wavefront detection resolution and the effect of detector signal to noise ratio (SNR) on the final measurement. Determining these two specifications for a given wavefront sensor is the primary goal of the AWESoMe testbed. Figures 1 and 2 provide a visual representation of the method for measuring the wavefront errors as well as the physical hardware required to do so.

2.2. Roddier Curavture Wavefront Sensor

Because the RCWS method is relatively new compared to the Shack-Hartmann array method there are no commercially-available sensors to use in the testbed. In addition to creating the test platform, this project will develop an implementation of the Roddier wavefront sensing method using available hardware.

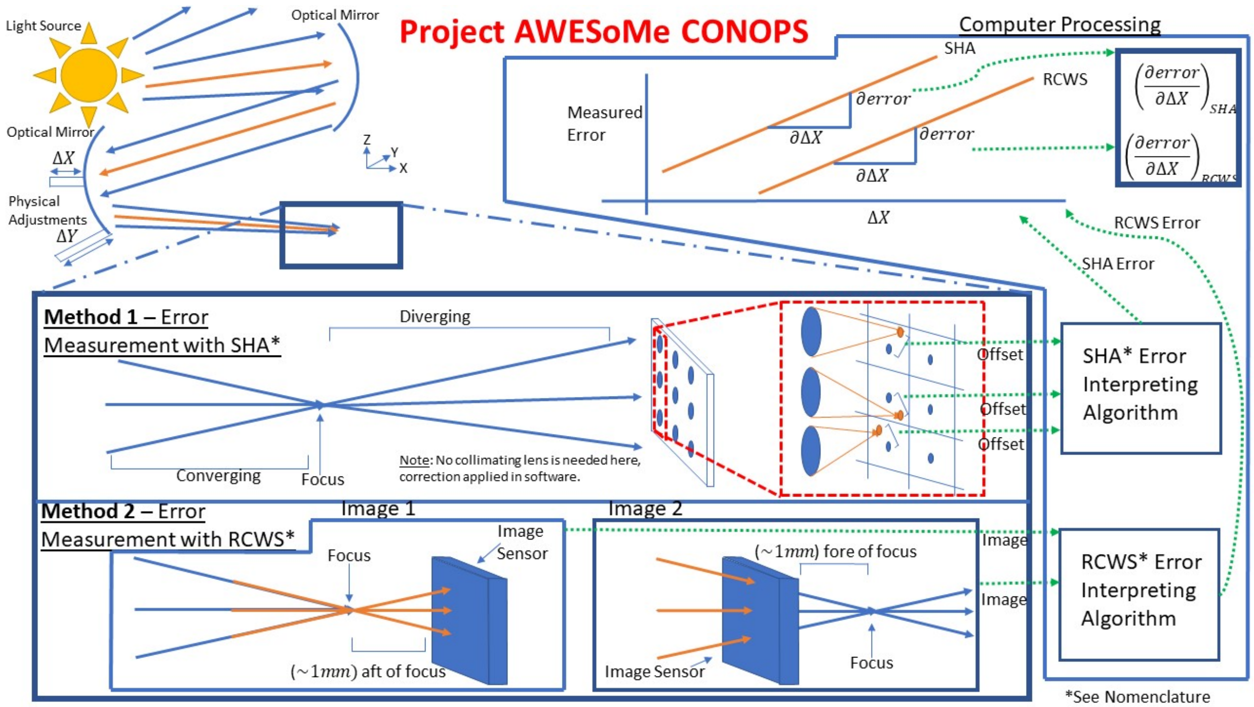

Figure 1: Project AWESoMe concept of operations

Fundamentally the method requires a description of the intensity of light at two different planes, both fore and aft of the focal point as well as the distance between those two planes. Figure 3 illustrates this method with planes P_1 and P_2 separated by the distance $2l$ and centered about the focal point of the system.

3. Methodology

Again, the objectives of the project will be fulfilled with two main systems: a testbed capable of generating the measurements required to compare two wavefront sensors and a custom implementation of the RCWS method. The solution for each portion will be discussed in detail in the following subsections.

3.1. Testbed

The testbed is designed to compare the performance of the two wavefront sensors based on their sensitivity to wavefront error and their performance with different signal to noise ratios. In order to test sensitivity to wavefront error the testbed must be able to introduce wavefront error in smaller increments than $\lambda/50$ RMS, the smallest error that can be detected by the reference sensor (a ThorLabs Shack-Hartmann Array). It must also be capable of varying the SNR at the sensors from 100 to 100/128. Finally, because of the large amount of data to be collected, the testbed must be able to perform data collection automatically.

The sub-systems that perform these functions are the optical path, image source, and software package.

3.1.1. Optical Path

The purpose of the optical path, shown in Figure 4 with M1 (right) and M2 (left) being the two parabolic mirrors involved with the optical path, is first to focus the image produced by the image source to the detectors and to introduce known optical errors. The second task, to introduce wavefront error, is more critical to the project. In order to effectively test the two sensors, the testbed must exceed the precision of the Shack-Hartmann Array sensor. The resolution of that sensor is $\lambda/50$ RMS error. Introducing optical error at a higher resolution makes it possible to test the capabilities of the Shack-Hartmann Array and possibly prove the greater accuracy of the RCWS if it does, in fact, pick up smaller introduced errors than the SHA is capable of detecting.

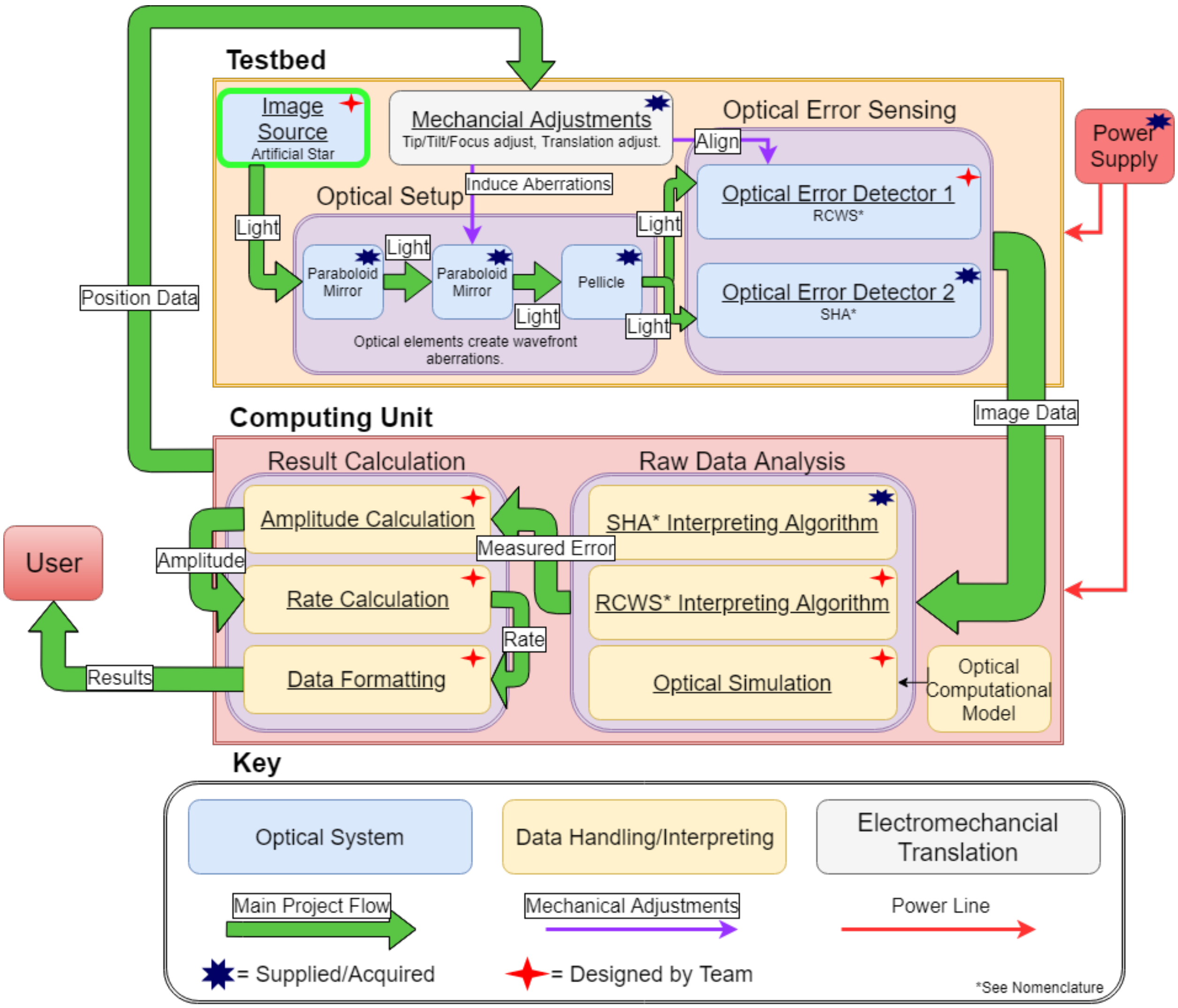

Figure 2: Project AWESoMe functional block diagram

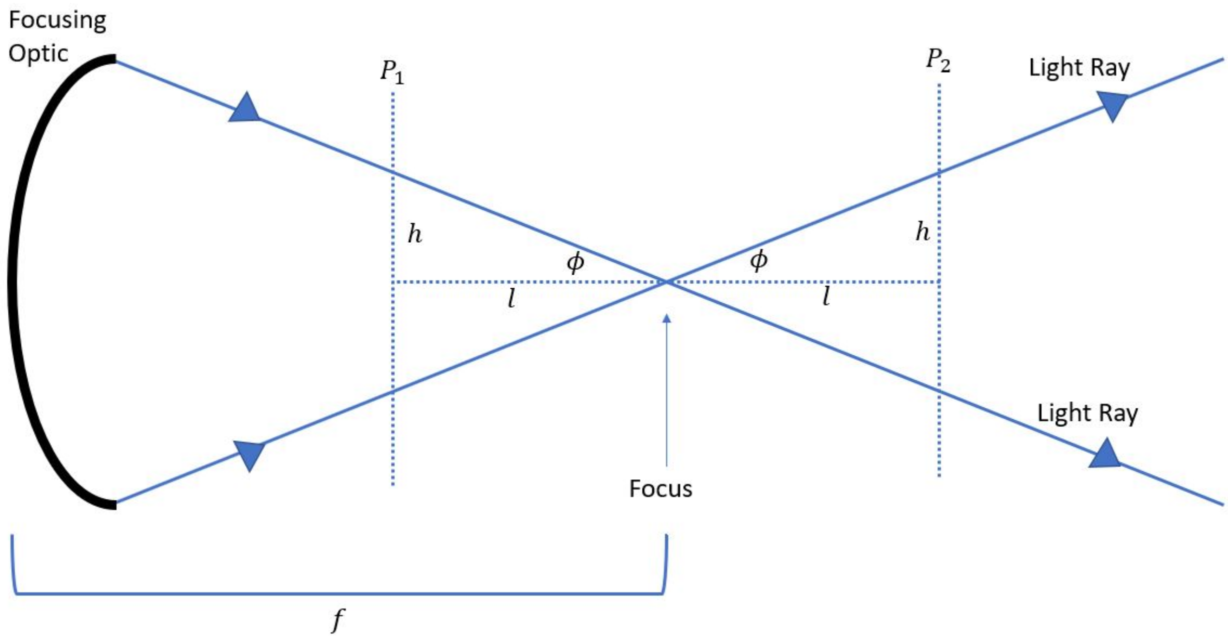

Figure 3: Roddier method of wavefront sensing

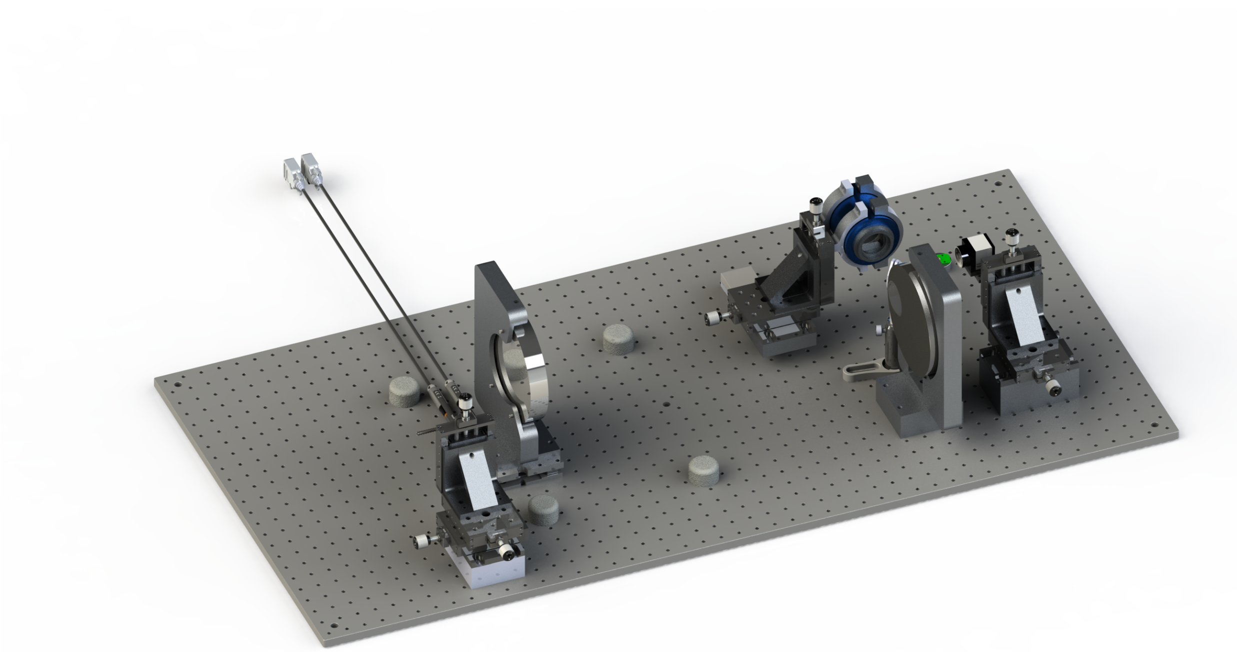

Figure 4: Dimetric view

Introduction of wavefront error is accomplished by rotating mirror M2 about the two non-symmetric axes: tip and tilt. Using a Zemax software model of the optical system, it was determined that the required tip and tilt resolution to introduce $\lambda/50$ RMS error to the wavefront is a 266 arc second movement in either axis. This motion is controlled by a ThorLabs PY004Z8 rotary stage. This stage is specified by the manufacturer to have a resolution of 7 arc seconds.

The actual resolution of this movement was tested by affixing a laser diode module to the stage. The stage was then commanded to move in the smallest step size and the resulting displacement of the laser recorded on a stationary image detector. The results of this test showed an average movement of 8.97 arc seconds with a standard deviation of 4.17 arc seconds. Though this number is greater than the specification from ThorLabs, it is still well below the required resolution to introduce $\lambda/50$ RMS wavefront error.

3.1.2. Image Source

Variation of the SNR begins with the image source which provides a known constant condition for the rest of the system. The source must be able to emit enough photons that the SNR at the longest shutter speed is at least 100. It must also remain stable over time so that varying the shutter speed of the detectors can be assumed to change the SNR in the expected manner.

The image source, shown in Figure 5 consists of an emitter, a condenser lens to increase intensity, and an optical fiber to transmit this light to the entrance of the optical system. The entrance, given in Figure 6, consists of a pinhole in order to form a spherical wavefront but this also causes a great reduction in the amount of light that passes into the system. The LED was chosen based on this restriction using a lost light analysis along the image path and the requirement that 600,000 photons must reach the image sensors each second. This analysis factored in the light lost through light not captured by the image rail optics as well as light lost in back-reflections and in passing light through the small pinhole. From this, it was determined that at least 80W of light would have to be emitted from the the light emitter to satisfy this requirement. A 100W LED was a reliable and compact choice to fulfill this requirement.

Variation of the SNR received is accomplished by modulating the shutter speed of the cameras. This changes the size of the expected signal while keeping noise sources such as shot noise and dark current approximately constant. This method effectively allows testing of a range of SNRs using pre-existing methods. Initial testing showed a standard deviation in the signal level output by the image source of 3%.

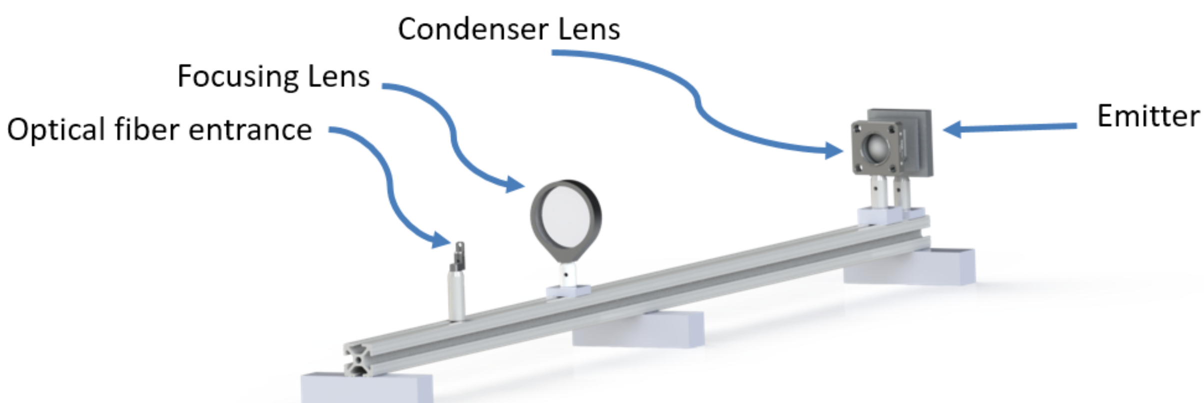

Figure 5: View of the main image source rail

3.1.3. Software

Because the set of data to be collected by the testbed includes variation of the wavefront, displacement of the RCWS, and the received intensity levels, there is a significant chance for human error to affect data collection. To expedite the test process and reduce error automation is required. Test automation is primarily accomplished by assuring software control of the motorized optical stages and the wavefront sensor image detectors.

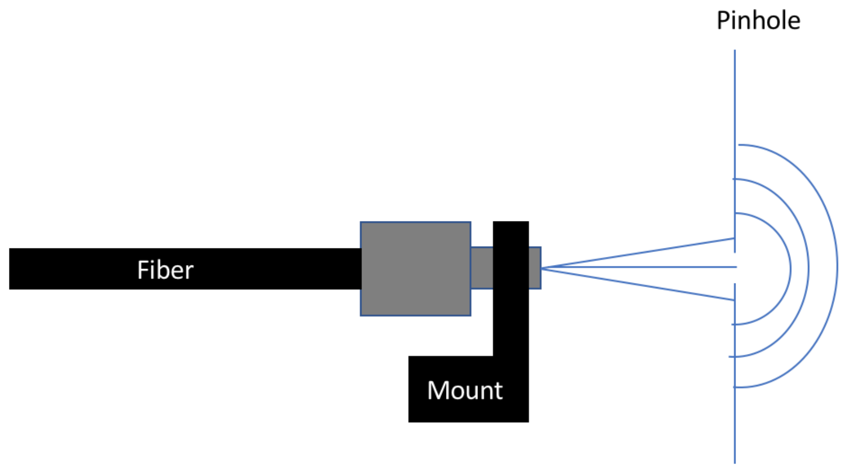

Figure 6: Second Image Source Sub-Assembly

Automation of the tip/tilt platform and linear traverse movements was by the ThorLabs KDC101 motor controller. ThorLabs provides an API interface that supports user-created programming. With this support, the test control computer interfaces with the motor controller and automatically commands the motorized stages according to a test specification file.

Test control also involves collecting the required images from the SHA and the RCWS. ThorLabs also provides a convenient API interface for the wavefront reconstruction software that comes with their model of Shack-Hartmann Array wavefront sensor. The team also used the ASCOM astronomical imaging program to interface with the RCWS detector programmatically.

These main elements, with the support of several smaller components, provide an effective method to automate data collection. Ultimately, this automation increases the reliability and quantity of data created using the testbed.

3.2. Roddier Curvature Wavefront Sensor

In addition to the testbed, project AWESoMe developed an implementation of the RCWS method using commercially available hardware. Ultimately the Roddier method requires:

1. An image sensor to take images fore and aft of the focus.
2. A method of moving the image sensor to the fore and aft locations of the focus.
3. An algorithm which takes the two images as an input and computes the wavefront based on these images using the Transport of Intensities equation (Eq. 1).

$$\frac{\delta I}{\delta z} = \frac{\lambda F(F-l)}{2\pi l}\Big(\frac{\delta}{\delta n}\phi\frac{F\vec{r}}{l}\sigma_c -^2 \phi\frac{F\vec{r}}{l}\Big) \tag{1}$$

These three elements were fulfilled in order to produce a test article RCWS. This sensor was then used in a data collection test. It is important to note that while the physical capabilities of the image sensor and linear traverse affect the performance of the RCWS, perhaps the largest factor is the implementation of the wavefront reconstruction software.

3.2.1. Image Sensor

To reiterate, the Roddier method uses the difference in intensities between images taken in front of and behind the focus of an optical system to reconstruct the incoming wavefront. Two image sensors were provided by the customer to be used in the RCWS. The quality of measurement of the intensities directly affects the quality of results obtained by the RCWS. Ideally, the intensity distribution would be known without error or discretization, however this is impossible. The two detectors provided have different sampling depths (8 and 12 bit) as well as different pixel sizes. In one case higher precision on the intensity value is offset by lower spatial resolution. For the other detector this relationship is flipped. Both sensors can be used in the final system to see which effect is most important to the RCWS method.

Regardless of the selection of the image sensor, the included software to drive the sensor is limited to manual exposure-setting and image-capturing. So in order to support long testing sessions and repeatability, the team created an automatic image-sensor control system, which will take in pre-defined camera settings, set these values on the image sensor, and take the image when necessary.

3.2.2. Linear Traverse

The second hardware component is the linear traverse. The purpose is to translate the RCWS fore and aft of the focus. Doing so enables finding the difference of intensities and ultimately reconstructing the wavefront. Some research has been done to determine the optimal defocus distance of the RCWS and the conclusion is that there is no single best location[2]. The optimal defocus distance is dependent on the particular optical system in which the sensor is used. To account for this the team chose to use the Thorlabs PT1-Z8 linear traverse. It has very fine 50 $[nm]$ movement resolution and a range of 25.4 $[mm]$. This allows finding the optimal defocus distance to be done experimentally. The PT1-Z8 is motorized by the same system as the tip and tilt platform of the testbed. This allows the test control program to easily interface with the linear traverse. This automated method of obtaining images fore and aft of the focus allows for an effective implementation of the second of three main components of the RCWS.

4. Conclusion

The purpose of project AWESoMe is to develop a testbed and RCWS sensor that could be used in the future to compare the performance of two wavefront sensing methods. The testbed was designed to introduce wavefront error in increments less than $\lambda/50$ RMS, vary the SNR received by the sensors from 100/128 to 1/128, and automate the data collection process. The RCWS implementation was required to provide an intensity map at two defocused image planes as well as the distance in between those planes.

Verification of the testbed proved that it far out-performed the required 266 arc second tip/tilt precision with a median step size of 8.97 arc seconds and a standard deviation of 4.17 arc seconds. Testing also showed that the image source had a standard deviation in total output of 3% over the course of 10 images, proving that it would be sufficiently stable to assume a direct relationship between the exposure time and signal-to-noise ratio. Finally a test automation scheme was developed and implemented to allow reliable collection of hundreds of data points. All this testing verification shows that the testbed has sufficient control over the introduced wavefront for an accurate comparison between two wavefront sensors to be made in the future.

An RCWS implementation was designed using an off-the-shelf CMOS image detector and optical linear traverse. This method provides both components of the transport of intensities equation (Eq. 1) that allows reconstruction of the wavefront using the Roddier method. The linear traverse was proven to repeatably position the image plane to within micrometers of the desired position, thereby minimizing error in the TIE.

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Overall, the project was successful in developing a test platform that provides the information required to compare the RCWS method of wavefront sensing to the Shack-Hartmann Array. This system will be verified as a whole in an upcoming trial data collection.

References

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