APPLICATION OF SHACK-HARTMANN WAVEFRONT SENSORS TO OPTICAL SYSTEM CALIBRATION AND ALIGNMENT

DANIEL R. NEAL,

WaveFront Sciences, Inc.; 14810 Central SE,; Albuquerque, NM 87123, USA
drneal@ wavefrontsciences. com

JUSTIN MANSELL,

Stanford University; Edward L. Ginzton Laboratory; Stanford, CA 94305, USA
jmansell@stanford. edu

Optical systems are normally aligned by centering the energy distribution in various apertures. However, the use of both irradiance and phase information can in many cases greatly simplify this process, and can provide information for closed-loop alignment and control of an optical system. This can be accomplished by using a Shack-Hartmann wavefront sensor for alignment and performance testing.

While Shack-Hartmann wavefront sensors are commonly used for adaptive optics, they have many other applications. The modern Shack-Hartmann wavefront sensor is compact, rugged, and insensitive to vibration, and has fully integrated data acquisition and analysis. Furthermore, even wavefronts of broadband sources that cannot normally be tested with interferometers can be measured with Shack-Hartmann wavefront sensors. The instrument also provides information about the optical system performance, including peak-to-valley (PV) wavefront deviation, RMS wavefront error, the modulation transfer function (MTF), and the point spread function (PSF). Since the difference of two wavefronts is easily computed, the effect of individual optical elements on a complex optical system can be examined.

In this paper we will present an alignment methodology using the Shack-Hartmann wavefront sensor to setup even complex optical systems. An example of using the methodology to align a lens is presented. Alignment of the Shack-Hartmann wavefront sensor to a 24-inch telescope at Stanford University is presented. The higher-order static aberrations in the telescope are then measured with the Shack-Hartmann wavefront sensor.

1 Introduction

Alignment of optical systems comprised of even the simplest components can often be a tedious difficult task. It is often difficult to assess the final accuracy of the alignment task, other than overall performance measures of the total system. In many cases it is difficult to tell which element is misaligned, and how to fix it. The application of interferometry to this task is often difficult since this usually requires double-pass testing of the optical system and alignment to the interferometer beam. The use of an interferometer can be especially difficult if the total optical path is long. A shearing interferometer can sometimes be used for optical element positioning; however, complex analysis is required to provide a quantitative interpretation of the aberrations and it requires the use of fairly narrow bandwidth sources. An autocollimating telescope provides a simple method for aligning an optical system, but, like the shearing interferometer, offers no easy way of extracting performance information. Clearly a means is needed for aligning and calibrating optical systems, especially with broadband sources. The Shack-Hartmann wavefront sensor was invented in 1971 when Roland Shack modified the Hartmann optical test by substituting an array of lenses for the array of apertures generally used for the test.[1] It was primarily developed in the successive two decades for use in adaptive optics systems, but recently has been commercialized for optical metrology.[2] The commercially available Shack-Hartmann sensor can be built in a compact rigid assembly, which makes it ideal for aligning and testing optical systems. The Shack-Hartmann wavefront sensor (SHWFS), shown in Figure 1, relies on an array of small lenses to create focal spots on a CCD. The motion of the focal spots is dictated by the average gradient of the wavefront over each lens. Thus the grid of focal spots can be used to provide a measure of the wavefront gradients across the entire aperture. These gradients can then be integrated to provide the wavefront of the incident radiation. More detailed documentation is available on the operation of the sensor in various sources[3,4] and will not be discussed here, but for later discussion of the sensor, we will introduce some terms associated with the sensor. The lens array creates a pattern of focal spots on the CCD. The CCD image is broken into subapertures (called Areas Of Interest or AOIs) of N x N pixels (corresponding to the region behind each lens) in which the spot position is determined: The algorithm usually used to determine the position of the focal spots on the CCD is called the first moment or centroiding. The size of the irradiance distribution on the CCD can be characterized by the second moment of the distribution.

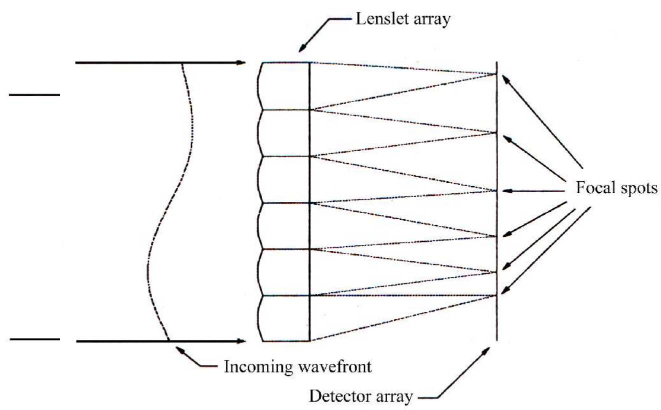


Figure 1 - Basic components of a Shack-Hartmann wavefront sensor.

There are several important advantages to using the Shack-Hartmann wavefront sensor for measuring the wavefront. Unlike many beam diagnostic systems, the instrument requires no moving parts. The incident radiation does not have to be coherent. The instrument provides a measure of both the irradiance and phase distributions of the incident light. The SHWFS acquires all of the information from a single CCD image, so short exposure times can be used to reduce sensitivity to vibration and pulsed sources may be analyzed and aligned. The processing of the CCD image is straightforward, simple, and may readily be performed on PC computers at high speed. Furthermore, the point-spread-function (PSF, modulation transfer function(MTF), Zernike wavefront decomposition[6], beam quality parameter' and other analysis parameters can also be performed. The SHWFS can be configured for a variety of aperture sizes, wavelengths, sensitivities and dynamic ranges. At WaveFront Sciences, Inc., we have integrated the SHWFS with the lenslet array, detector, electronics, data acquisition, control and analysis software into a single package which we call the Complete Light Analysis System (CLAS-2D)[8].

The key advantage of a SHWFS for optical alignment is that it provides a measurement of both irradiance and phase distributions. This information can be displayed in such a way as to make the alignment of optical systems quite easy. The body of this paper will describe the methodology of this process and will present some examples of the application of these methods to various optical systems.

2 Alignment of optical systems

For any optic in a system, there are various degrees of freedom commonly used to align an optical system. These include centering, tilt angle, and optical element rotation. Misalignments in any of these degrees of freedom will result in optical aberrations. Unfortunately, many of these aberrations are highly coupled, so it is difficult to adjust any one degree of freedom without adversely affecting other parameters.

As an example of this, consider the alignment of a simple lens used to collimated a point source. In this case there are five degrees of freedom: x-y centering of the intensity distribution, tip/tilt (or angle of arrival) of the distribution, and focus. However, errors in any of these parameters will result in aberrations that may be highly coupled. For example, de-centering of the lens results in both a translation of the intensity distribution and a tilt of the resulting wavefront. It also introduces an apparent rotation of the lens that can affect the collimation and astigmatism of the wavefront.

One of the convenient features of the CLAS-2D Shack-Hartmann wavefront sensor system is that important parameters for optical alignment are presented in a simple graphical form. A simplified example the graphic interface is shown in Figure 2. In this case, an ellipse represents the irradiance profile. The position of the ellipse represents the position of the centroid of the beam. The size of the ellipse represents the size of the beam on the sensor. The major and minor axes of the ellipse can also easily be calculated by computing the cross moment. The average tilt is shown as a vector whose center is the center of the ellipse, its endpoint represented by the average tilt. An arbitrary scale factor is applied to the average tilt since it has different units in general from the position information.

These few parameters can be acquired, computed and displayed extremely fast. 5-10 Hz is routinely achievable, even for highresolution sensors and slow computers. This allows adjustment of optical components in the optical train with near real-time feedback. This greatly speeds up the alignment process and makes possible an automatic alignment.

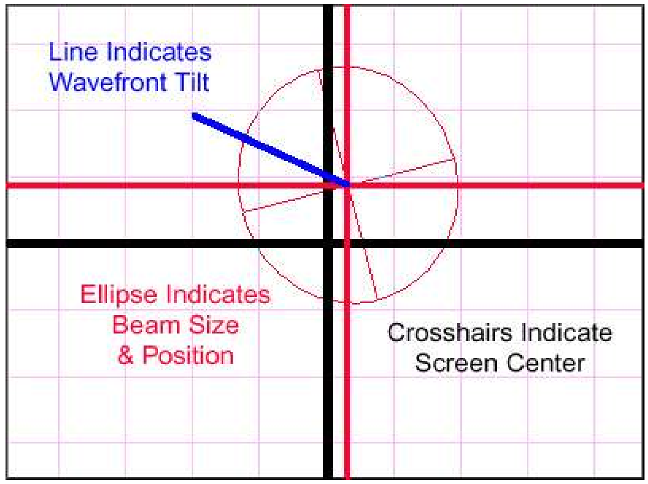


Figure 2 - Simple graphical representation of average tilt, beam position, and beam size, and beam ellipticity.

There is one drawback to the above representation. It is difficult for the user to tell from this display when the wavefront aberration has exceeded the dynamic range of the instrument. Usually the dynamic range is defined as the range of input angles for each AOI where the focal spot remains completely behind one lens. There are AOI tracking methods that may be applied to improve the dynamic range, but these are not usually applied to the initial alignment step. While this drawback may seem limiting, in practice it is fairly easy to identify and overcome. Adding sufficient tilt to exceed the dynamic range causes rapid, wild swings of the tilt vector.

We have found that the following sequence of steps is useful for achieving optical alignment with the SHWFS:

1. Position apertures or otherwise define the optical axis.

2. Position the SHWFS as the last element in the optical train. Align the sensor to be accurately centered (minimize (x,y)), and oriented orthogonal to the optical axis (minimize θ_x, θ_y).

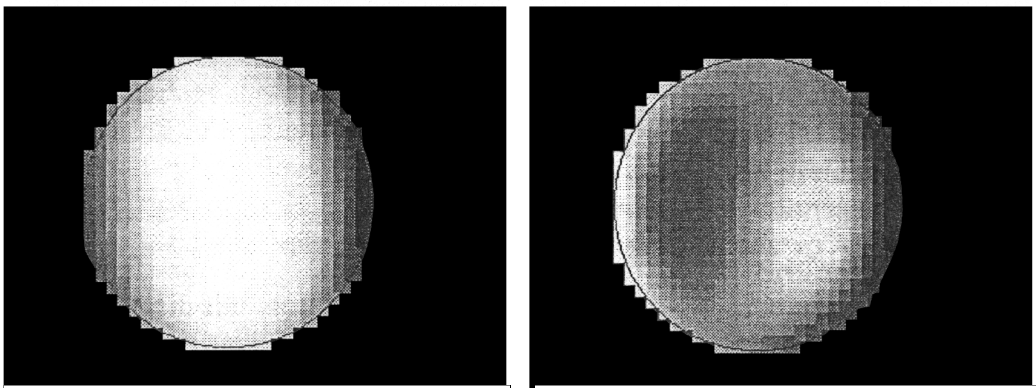
3. Insert optical elements one at a time. Align each element to re-center the irradiance distribution and minimize the average tip/tilt.

4. Collimate the system as required by minimizing the RMS or P-V wavefront error. This requires the use of the full wavefront produced by the SHWFS.

5. Optimal element rotation can be achieved by adjusting the rotation iteratively, while assuring that the centering and tilt are maintained.

Note that this sequence has been described for multi-lens telescopes, where the final leg is designed for a collimated space. Where this assumption is invalid, it may be necessary to use a recollimating lens. By pre-recording the appropriate reference, aberrations in this lens may be subtracted.

Step 5 in the above list relies on an additional property of real optics. Consider the case of a doublet that is significantly rotated, as shown in Figure 3. In this case, numerous aberrations are introduced. The chief aberrations are astigmatism and defocus, although tilt, coma, spherical aberration and other terms may be present. However, if the initial irradiance distribution was centered on the SHWFS before inserting the lens, this position records accurately the average values. All of the



F/5 lens, rotated -15°, large astigmatism and defocus

F/5 lens, rotated -15°, Even terms subtracted

Figure 3 - Aberrations for an F/5 lens rotated 15°. Note that the odd terms will results in a net average tilt.

even terms will be exactly symmetric (by definition) about this location. Hence they will have an average net tip/tilt contribution of zero. Only the odd terms will have a value. The presence the coma term, however, is small for simply decentered lenses, and is only significant when the lens has rotation. Thus it is possible to identify the condition (i.e. decouple the degrees of freedom) where the lens has minimum rotation and is accurately centered. This will result in a well-centered intensity distribution and minimum tip/tilt. Any other condition (decentered plus compensating rotation) will not allow both conditions to be simultaneously met. The experimenter may align the lens by adjusting the rotation in small steps, recentering the irradiance distribution between each one. When both the minimum tip/tilt and centration have been achieved, the optic is correctly aligned.

Once the optical system has been aligned, the SHWFS can also be used to measure the residual higher-order aberrations. Many different analysis functions can be performed, including Zernike decomposition, fringe display, point spread function and modulation transfer function. An example of using the wavefront sensor to characterize an existing optical system is presented in the following section.

3 Alignment and measurement of a 24" telescope

As an example of this process, this section presents the results of aligning and measuring the performance of a 24 inch diameter Cassegrain telescope at Stanford University. In this case, the SHWFS was mounted directly on the telescope with the addition of a single 50mm collimating lens. The SHWFS used was comparable in weight to the eyepieces used by the telescope, so did not appreciably affect the balance or weight load on the telescope. The process described above was used to align the system with a bright star (Arcturus) as a reference. Since this telescope operates almost at sea level, there was a significant amount of turbulence present during this process. Nevertheless, it was a straightforward matter to install, align and collimate the collimating lens and the wavefront sensor. Once installed, the sensor was used to record many images of different stars. Since the version of this sensor was not designed especially for low-light conditions, only a few bright stars were examined.

After the basic alignment was achieved, the telescope was characterized using the SHWFS. A plane-wave reference was pre-recorded in the laboratory using a wellcollimated HeNe laser beam. Since we were interested in evaluating the telescope and not the atmospheric turbulence, 30 frames were taken at 1 second intervals and the images were averaged together. By comparing the plane-wave reference and the averaged image data, a measure of the telescope optics were made. Figure 4 shows one such measurement. Another measurement was preformed after rotating the SHWFS and the lens by 90 degrees to make sure that the aberrations measured were indeed in the telescope and not in the wavefront sensor or the collimating lens. The two measurements were almost identical.

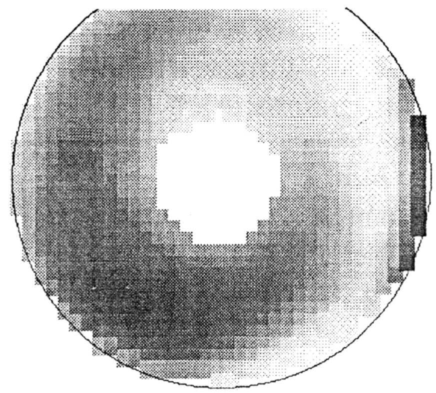


Figure 4 - Average aberrations of the 24-inch telescope. The P-V wavefront error is 3.6 λ. The wavefront was computed using a plane wave reference

4 Conclusions

In this paper we have argued that the Shack-Hartmann wavefront sensor is a good choice for measuring the alignment of optics because of its vibration insensitivity, broadband light performance, and ease of use. We introduced an iterative method for using the sensor to quickly achieve good alignment of an optic. We used this method to test a doublet in the laboratory and to align the Shack-Hartmann wavefront sensor to a 24" telescope at Stanford University. Once properly aligned, we used the Shack-Hartmann wavefront sensor to determine the higher-order aberrations in the telescope. The Shack-Hartmann wavefront sensor determined to be a valuable tool for characterizing the alignment of optical elements and the performance of even a complex optical system.

5 Acknowledgements

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