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ABSTRACT

The addition of a piezo-electric focusing stage and phase retrieval algorithms to a compact, adaptable autostigmatic microscope provides for both improved focus sensitivity during optical system alignment as well as the ability to measure low-order aberrations for system qualification. A description of the instrument and initial results are reported.

Keywords: autostigmatic microscope, autocollimator, optical alignment, adaptable alignment module, point source microscope, phase retrieval, wavefront measurement, aberrations

1. INTRODUCTION

Autostigmatic alignment tools are well known [1]. The autocollimator (AC), which is an autostigmatic telescope, is perhaps better known than an autostigmatic microscope (ASM). Even so, autostigmatic microscopes are in rather common use. One can think of an autostigmatic microscope as a finite conjugate version of an autocollimator. An autocollimator is used to measure the direction of a surface normal, a measurement which defines two degrees-of-freedom. An autostigmatic microscope is used to locate the center-of-curvature of a surface, which defines three degrees-of-freedom. One instrument type is not necessarily better than the other in general; however, one may be much more appropriate than the other depending upon the task at hand.

An adaptable alignment module was described in a previous paper [2] by the author. The module with its standard 100 mm focal length collimating lens and 10x objective installed is shown in Figure 1 below and functions as an autostigmatic microscope. Removal of the objective allows the instrument to operate as an autocollimator with a nominally 12 mm diameter beam. The collimating lens is interchangeable and customizable to meet different requirements such as beam size.

Figure 1. W2 alignment module with 100 mm focal length collimating lens and Nikon 10x objective installed. Removing the objective exposes a 12 mm diameter collimated beam with the standard 100 mm focal length collimating lens.

In this paper a closed-loop, piezo-electric translating stage is mounted between the collimating lens and objective to provide controlled defocus. This modification, along with the additional of phase retrieval software produces an instrument that is able to measure low-order aberrations. Measurements of low-order aberrations can be used in critical alignment tasks and provide data to qualify many optical systems without the need for an interferometer.

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2. ALGORITHM OVERVIEW

2.1 Background

If one looks at an image of a point source (i.e. performs a star-test) of a system it is often possible to discern the difference between an image of a point source that is good enough and one that not. Moreover, if one is suitably trained it is possible to discern what aberrations are present. When performing a start test by eye, almost invariably one would learn to move through focus to help discern which aberrations are present. Phase retrieval is a means of taking images and quantitatively measuring the wavefront, not just discerning. The need for more than one image to recover phase is due to the loss of phase information in the detection process.

Usually the input images to a phase retrieval algorithm have some amount of phase diversity, typically defocus, between the images. Phase retrieval algorithms operate in either a geometrical or physical optics domain. In the physical optics domain, the amount of defocus is small, and the image is behaves like a defocused version of the image plane and diffraction theory is incorporated in the solution approach. In the geometrical optics domain the amount of defocus is large enough that the input images are more like an out-of-focus pupil image, rather than a focal plane image, and the solution approaches may make use of the intensity transport equation.

2.2 Motivation for the approach

The W2-AM instrument is a simple and practical alignment tool. As such, the W2-AM is usually used to look at image planes, including both system image planes as well as image planes at the center-of-curvature of optical surfaces. By its nature, the W2-AM wants to look at images, not pupils. As a result of the intended use of the W2-AM in ASM mode a physical optics approach using small translations to introduce the required defocus for phase retrieval makes sense and can be well accomplished by a piezo-electric focusing stage for microscope objectives.

Another consideration in the use of phase retrieval with the W2-AM is to realize that if the spot size of a system is somewhat larger than the Airy disk diameter, then the system can be qualified by measurement of spot-size and phase retrieval methods may not be necessary. It is only when the performance of the system is such that the ideal spot size is close to or not much larger than the Airy disk size and has only a few pixels across it that phase retrieval is a good match. The reason is simply that defocus spreads the spot out enough to obtain useful information for phase retrieval while the small spot size at focus allows the instrument to have a large field-of-view making alignment easier.

A practical goal for an ASM used also for wavefront measurement is to be able to reliably differentiate between a system that is perhaps a 1/4-wave and $1/10^{th}$-wave, and maybe even a $1/20^{th}$ wave. What is not needed is much resolution across the pupil of the system. In other words, a 100-pixel by 100-pixel measurement of wavefront is not needed to qualify most optical systems, but such a measurement, or better, is often needed when fabricating components.

In summary, the approach is to use small amounts defocus and software to determine low-order aberrations of a system under test. This implies working in the physical optics regime. Finally, the approach is intended to address alignment and system test problems, but not optical component fabrication.

2.3 Algorithm overview

The phase retrieval method is based upon a constrained, non-linear optimizer. Inputs to the phase retrieval process (wavefront reconstruction) are:

1. a pair of defocused images
2. wavelength,
3. numerical aperture of the light cone at the objective,
4. displacement distances from nominal for the pair of images, and
5. a cost function.

The cost function calculates a scalar measurement of the difference between the predicted image based upon a set of Zernike coefficients and the acquired images. The Zernike coefficients are evaluated on a grid representing the exit pupil wavefront. This information, along with a description of the amplitude in the pupil is used to calculate an estimated image for both positions via wavefront propagation in the Fraunhofer region via what is essentially a two-dimensional FFT. The optimizer adjusts the Zernike coefficients to minimize the cost function.

3. SIMULATED DATA

3.1 Overview

The W2-AM with a 10x objective and silicon nitride tooling ball was modelled in Zemax™. The actual design of the instrument was used along with ½” diameter tooling ball as the test object. The 10x objective lens was represented as “perfect” (i.e. paraxial) lens in Zemax with a 20 mm focal length. Zemax was used to calculate diffraction images for a point source for the nominal focus, and the two displaced focus values to simulate the motion of the PZT stage. The system model starts at the point source, out through the objective, to the tooling ball, back through the objective and to the camera. In the actual device, the source path is reflected at the beam splitter interface, but for this analysis that detail was ignored, the model is however complete in double-pass from source to unit-under test (the tooling ball) to camera.

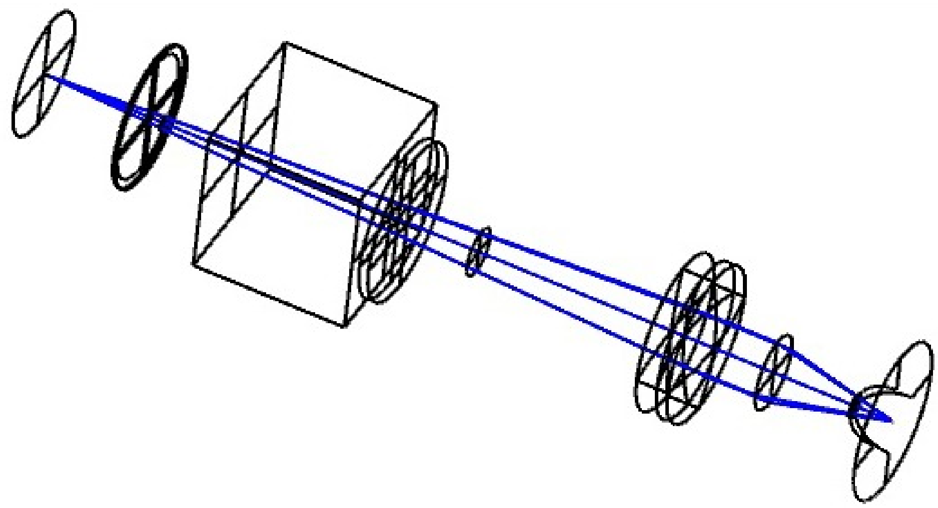

Figure 2. Zemax layout of the model used to produce simulated image data.

Various perturbations were introduced into the simulation. A Zernike phase surface was added at the paraxial lens, and is encountered twice in the simulation. Additionally the tooling ball was offset axially and transversely for various situations. The text (data) version of the predicted images were saved and then imported into the Aligner PR program that runs the W2-AM-PR. As a practical matter Zemax actually performed the simulations with far smaller pixels than on the camera. The pixel size in Zemax was set such that it was an integer ratio to the 3.45 μm pixel size of the camera. The analysis software simply summed pixels from the input data to create data for analysis such that a 4x4 pixel from Zemax became a pixel in the software.

3.2 Individual and mixed Zernike coefficients

Individual Zernike coefficients from focus to spherical were simulated in Zemax and analyzed in the Aligner PR software. Additionally a mixed set of coefficients were analyzed.

In Table 1, the results of simulations of individual coefficients are shown. The first entry is a null, or zero input for all aberrations. Even so, the system has a small amount of spherical aberration and Zemax calculated a 2.8 nm rms wavefront error. The simulated data was used by Aligner PR to reconstruct the wavefront with an estimate of 2.65 nm rms wavefront error using Zernike coefficients 4 – 11 (Table 1, Index 1). Each entry, other than the first, in Table 1 corresponds to a simulation with a single non-zero Zernike coefficient on a “Zernike surface” and the resultant value for that coefficient from both Zemax and Aligner PR using the Zemax simulated image data.

Table 1. Analysis of Zemax simulation data.

			Zemax	Zemax	Zemax	Aligner	
Index			Zernike	Fit	Fit	Fit	Difference
			waves	waves	nm	nm	Nm
1	Null input		0	0.0044	2.8	2.65	0.15
2	focus	Z4	0.10	0.1987	126.2	129.1	2.9
3	ast	Z5	0.10	0.1993	126.6	123.7	-2.9
4	ast	Z6	0.10	0.1993	126.6	124	-2.6
5	coma	Z7	0.10	0.1990	126.4	96.7	-29.7
6	coma	Z7	0.05	0.0995	63.2	60.5	-2.7
7	trefoil	Z9	0.10	0.1990	126.4	129.2	2.8
8	trefoil	Z10	0.10	0.1985	126.1	128.5	2.4
10	sph	Z11	0.10	0.1936	122.9	123.6	0.7

All the values in Table 1, save one for coma, are within 3 nm of the Zemax value in a double-pass system. The following images show a few examples that worked well, and one that did not (Figure 5).

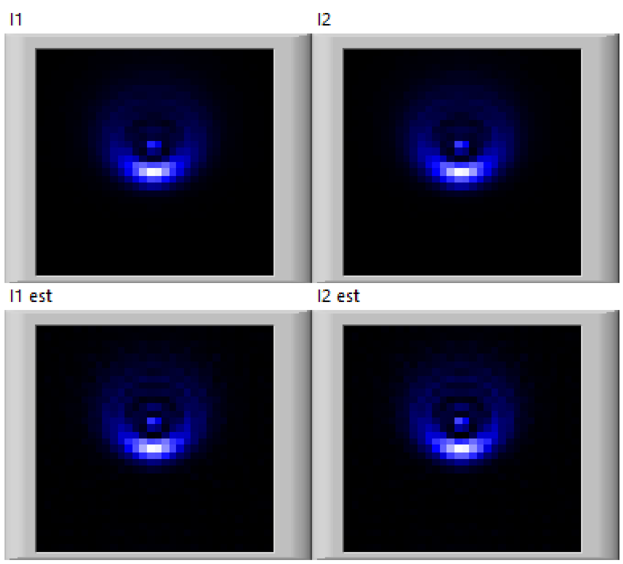

Figure 3. The top two pictures above are images I1 and I2 from Zemax for 0.05 waves of coma (Z7) viewed in Aligner PR. The bottom two images are the estimated images produced by Aligner PR. These images correspond to index 6 of Table 1.

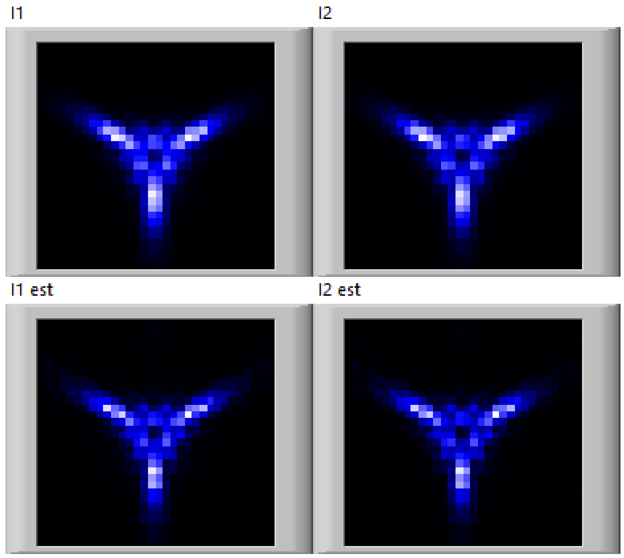

Figure 4. The top two pictures above are images I1 and I2 from Zemax for 0.1 waves of trefoil (Z8) viewed in Aligner PR. The bottom two images are the estimated images produced by Aligner PR. These images correspond to index 7 of Table 1.

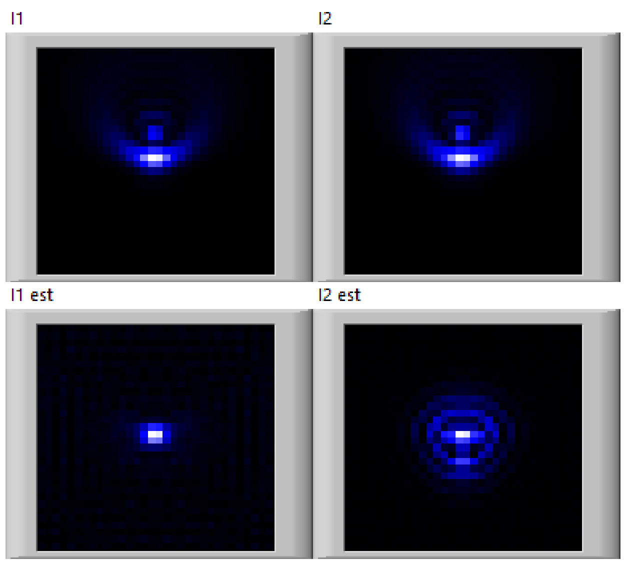

Figure 5. The top two pictures above are images I1 and I2 from Zemax for 0.1 waves of coma (Z7) viewed in Aligner PR. The bottom two images are the estimated images produced by Aligner PR. When there is a problem, it is generally, obvious. A better starting point or a smaller value results in the correct value being found. These images correspond to index 5 of Table 1.

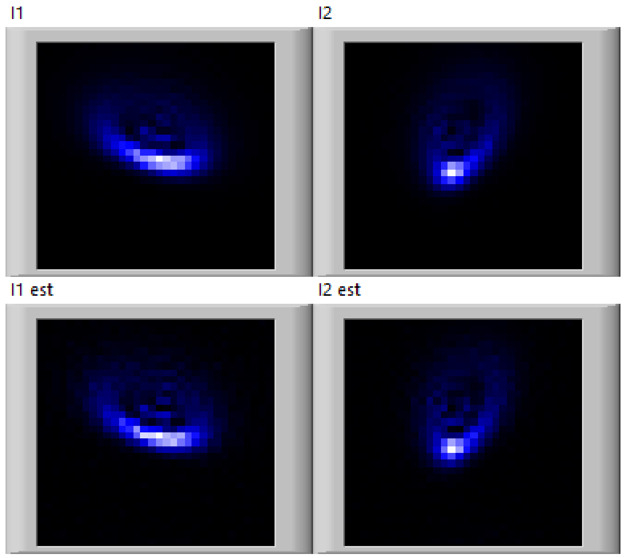

Figure 6. The top two pictures above are images I1 and I2 from Zemax for a mixture of coma and astigmatism viewed in Aligner PR. The bottom two images are the estimated images produced by Aligner PR.

Figure 6 shows the result for a simulation of mixed coma and astigmatism. The three non-zero coefficients results had differences of 2.1, -0.4, and 4.3 nm from the expected values from Zemax.

4. MEASUREMENTS

4.1 Measurement noise

Three sets of 100 measurements each were taken of a ½" diameter tooling ball. Nothing was moved between measurements. All measurements were taken in a standard office on a cart with the air conditioner running. The only change between each of the three measurement sets was the number of images that were averaged at each of the two defocused positions: 1, 10, and 100. The total RMS wavefront using Zernike coefficients 4 through 15 of the system was calculated for each measurement in each of the three sets. The mean and standard deviation of the RMS for the specified coefficients is shown in Table

Table 2. Measurement repeatability for averaging 1, 10 and 100 images at each position. RMS value is the wavefront considering Zernike coefficients 4 – 15.

# Images averaged		**RMS nm**
1	Mean	52.9
	Std dev	1.4
10	Mean	51.9
	Std dev	0.3
100	Mean	49.5
	Std dev	0.8

The value of interest in Table 2 is really the standard deviation of the RMS value for the three cases. In all cases it is quite low. However, there is a substantial benefit to doing a little bit of image averaging. Collecting 10 instead of 1 image at each of two locations only adds about (2*9)/30 seconds, or about 0.6 seconds to the data collection and a very low standard deviation of the wavefront measurement of only 0.3 nm. Clearly 100 images are too many.

4.2 Simulated and measured transverse ball shift

Transverse displacement of a ½" diameter tooling ball was simulated in Zemax at x-positions of 0, 0.25 mm and 0.30 mm. The primary aberration affected by this motion, is Z6, astigmatism. Table 3 below shows the results of the simulation in Zemax and measurements with the W2-AM-PR.

Table 3. Ball shift data, Z6

dx	Zemax	Zemax	Measured	Change	Error
mm	waves	nm	nm	nm	nm
0.00	0.000	0.0	-36.0	0.0	
0.25	0.252	159.9	120.3	156.3	-3.6
0.30	0.363	230.5	191.1	227.0	-3.5

Because the W2-AM-PR had a non-zero value on-axis, differences between the 0.25 and 0.30 measurements and the measurement at the origin were calculated. Those values were then compared to Zemax calculations of the expected astigmatism introduced by shifting the ball and a perfect objective. The real objective is not quite perfect; however, the measurements of Z6 differ by a nearly constant value of -3.6 nm (RMS wavefront) from the simulated values. In other words, the predicted change in the wavefront was measured with a trivial amount of error.

4.3 Focus measurement as a function of axial shift

A measurement of focus and astigmatism was performed as a function of the nominal axial position. Axial position was changed in steps of 1 µm. The measurements were performed with an average of 10 images taken at each position. The value of Zernike coefficients 4 through 6 are plotted below.

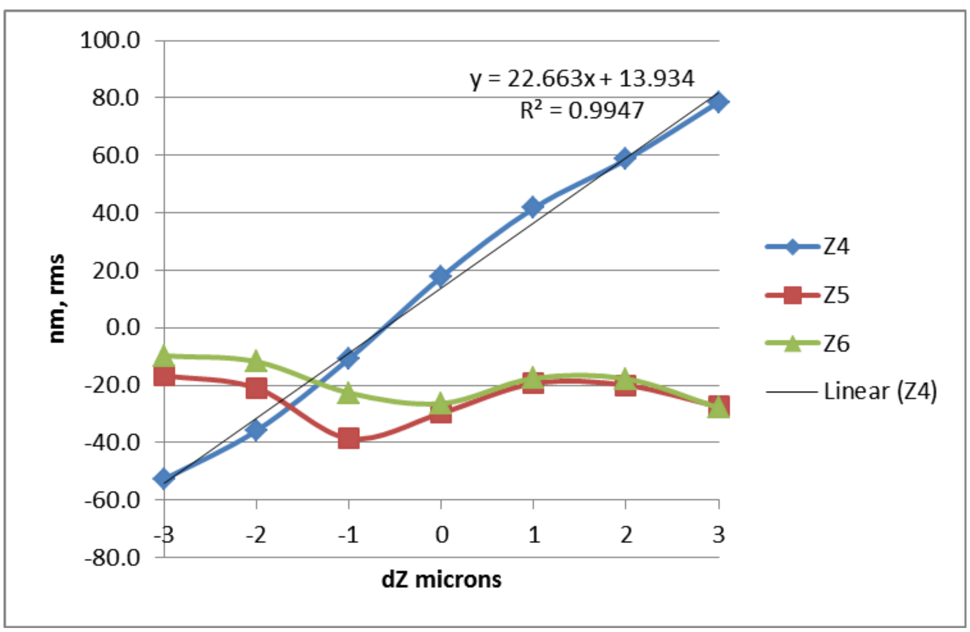

Figure 7. A plot of Z4 (focus) and astigmatism (Z5 and Z6) as a function of the nominal stage focus position.

A fit to the data provides an estimate of 22.7 nm/µm for Z4, the focus term. If the fit is just to values from -1 to 1, the slope is 26.2 nm. Zemax was also used to calculate the value of Z4 at dZ of 0 and 1, and a slope of 25.9 nm/µm of shift was estimated. Finding best focus with minimum wavefront residual will be possible to substantially less than 1 µm by taking advantage of the closed loop piezo stage.

4.4 Random ball test

A random ball test [5] was performed with the ½" diameter silicon nitride tooling ball. Because the system has a large field-of-view, the ball was only supported in a ring, rather than a strictly kinematic mount. The ball position moved a few microns between measurements. Even, so a calibration of Z4 through Z11 was able to be performed. Piston (Z1) is never fit in this instrument. Tip and tilt (Z2 and Z3) are somewhat arbitrary since the centroid of the measurement is used to find the spot for measurement and the ball was not on a kinematic mount and so are not calibrated.

Table 4. Random ball calibration results for Zernike coefficients 4 – 11 using 10 measurements.

(nm)	focus	ast	ast	coma	coma	trefoil	trefoil	sph
	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11
mean	20.8	-16.0	-24.5	-3.9	16.0	-5.9	5.9	2.4
max - min	64.7	22.7	23.2	9.4	5.7	7.7	12.3	13.8

The mean value in Table 4 represents the calibrated wavefront of the instrument. The max – min values are the range of each coefficient that was found over the set of 10 measurements.

5. SUMMARY AND CONCLUSION

The measurement of low-order aberration via phase retrieval has been demonstrated using the W2-AM-PR. The current device is appropriate for use with moderately fast optical systems. The tests were performed at 635 nm; however, different wavelength instruments are available. This is quite significant for systems that must be tested at wavelengths for which an interferometer is not available.

The repeatability is quite good and is more than adequate to be used in alignment and qualification of many optical systems.

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