COMPLEMENTARY ASPECTS OF OPTICAL ALIGNMENT AND IMAGE SYMMETRY

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INTRODUCTION

Almost all optical elements and systems are symmetric about their optical axes which means there are only 5 degrees of freedom that will affect optical alignment. Likewise, stigmatic images of a point source of light imaged by a finite conjugate optical system have 5 types of symmetry. There is a part of the image that is symmetric about the centroid of the image, and there are 4 symmetries in the plane of the image, namely, even-even, odd-odd, even-odd and odd-even. We show there is a one-to-one correspondence between the image symmetries and the degrees of freedom optical elements can be moved to align them.

There is little point is discussing the kinematics of locating an object with an axis of symmetry in space. Five degrees of freedom, 3 in translation and 2 in angle are all that are needed to completely define the location. Less obvious are the symmetries of stigmatic images, those formed by an optical system of one or more lenses or mirrors of a perfect point source of light, or infinite source like a star. Again, the image has 5 degrees of symmetry, 3 in translation and 2 in angle since the 6th is in the plane of observation and assumed perpendicular to the direction of propagation.

To illustrate our point, we consider the case of aligning an off-axis parabola (OAP) to an optical flat so that the normal to the flat is parallel to the axis of the OAP, the requirement for perfect alignment of the OAP. To view the aberration due to misalignment we use an autostigmatic microscope although an interferometer could also be used with the Zernike polynomial coefficients to show the image symmetry.

EXPERIMENTAL TEST SETUP

The hardware test setup is shown in Fig. 1 and a scale schematic diagram is shown in Fig. 2. The OAP used is a commercially available Thorlabs 1” diameter, 90°, diamond turned, OAP with a 2” focal length. The OAP was mounted in a holder capable of adjustment in 5 degrees of freedom (DOF). The return flat mirror had 2 adjustments for tip and tilt while the autostigmatic microscope (ASM), a Point Source Microscope (PSM) [1] in this case, had 3 degrees of translational freedom. While the OAP could have been used for the adjustments it was easier and more repeatable to use the adjustments on the flat and PSM. For the PSM we had digital micrometers on the focus and x-axis adjustments.

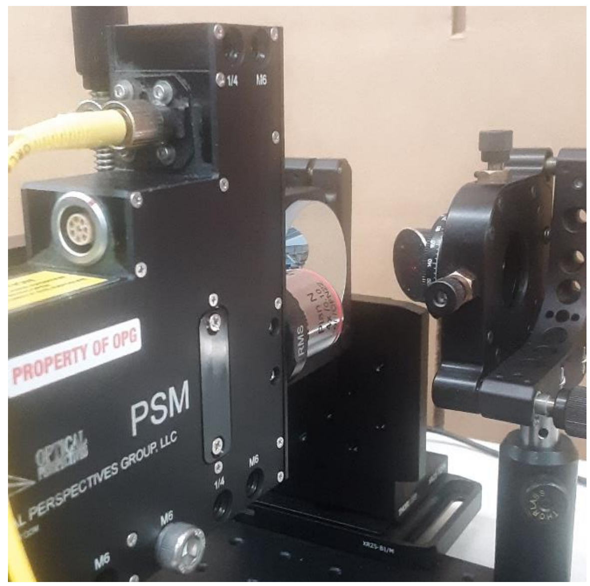

FIGURE 1. Hardware in the experimental setup

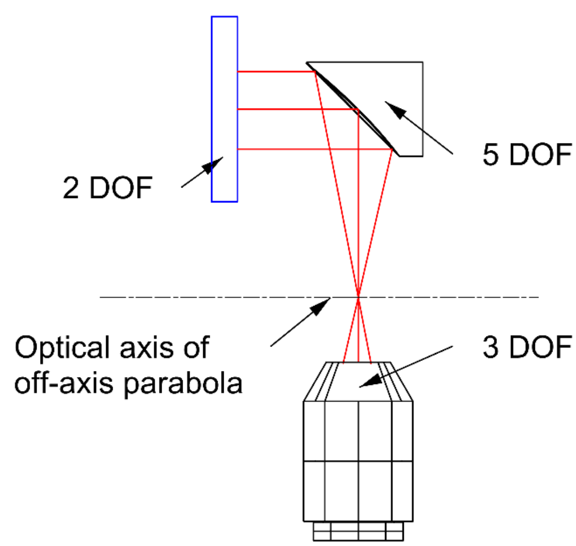

FIGURE 2. Schematic top view of setup

As an aside, one could reasonably ask why such alignment could not be done by using mechanical and optical datums such as centers of curvature or foci. As will be shown, μm level positioning errors can be seen in the image, and it is difficult except under very well controlled environments to make repeatable μm level measurements even with the datums built into items such as this OAP. Also, other possible datums are missing such as the OAP vertex, or difficult to impossible to reach as the part is mounted. It was necessary to use aberrations to guide alignment in this case. Ultimately, alignment by aberrations more closely matches the use of the optic in question. For example, OAPs are often used to couple light into or out of optical fibers and good image quality as well as knowing precisely where the image is located are essential to best performance.

IMAGE SYMMETRIES

An image as seen with a digital camera is a 3 dimensional topographical map with a 2 dimensional extent in the x-y plane of the detector and having intensity values perpendicular to the x-y plane as in Fig. 3 where this is just a 40 pixel square patch of intensities of a well-focused image from a megapixel camera on the PSM.

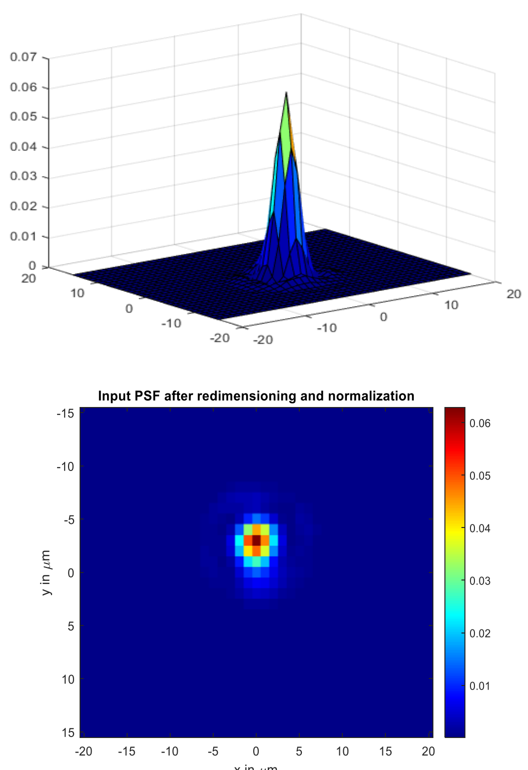

FIGURE 3. 3-D image profile (upper) and corresponding 2-D color map (lower).

This image has one symmetry component that does not vary with azimuth when rotated about the central pixel that we define as the rotationally symmetric part of the image. To find the other 4 symmetry components in the x-y plane we least squares fit the image in Fig. 3 with a 3-D rotationally symmetric Gaussian function to find the x_0, y_0 centroid of the Gaussian, and then subtract the Gaussian from the input image. This difference, or residual, map of intensities contains all 4 of the rotationally asymmetric components in the x,y plane.

Clearly, for a well-focused point image most of the energy is in the symmetric portion of the image. When you align an optical system the goal is to maximize the energy in the symmetric portion of the of the image and minimize the asymmetric part. The optimum situation for the symmetric degree of freedom, or for the best focus condition, is for the Gaussian to have a maximum amplitude and minimum FWHM diameter.

After subtracting the Gaussian fit from the input image in Fig. 3, the asymmetric portion is as shown in Fig. 4. The asymmetric part is centered about the centroid of the fit by clipping the size of the data set to an even, square matrix of data.

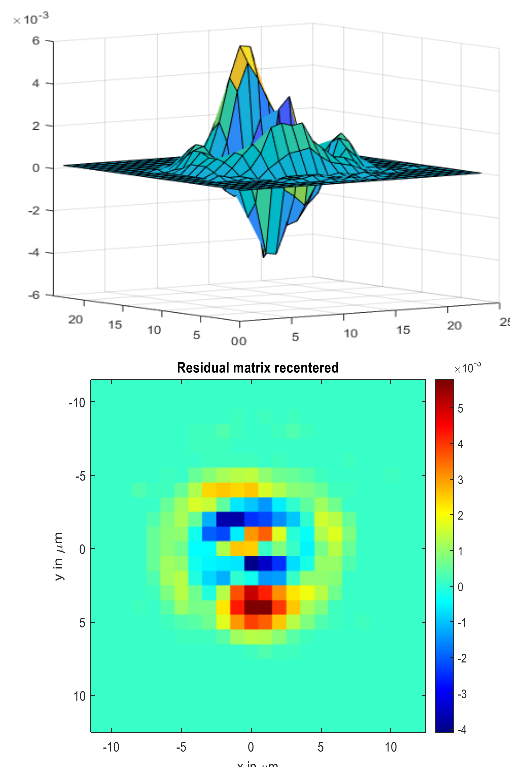

FIGURE 4. The asymmetric portion of the image as a 3-D profile (upper) and colormap (lower).

It is clear that the asymmetric portion of the image is much smaller than the symmetric from the difference in the colorbar scales on the maps in Figs. 3 and 4, and that the difference gives negative values to what are nominally intensities. To find the total energy in each symmetry group we use the sum of the square of the intensities at each pixel. The asymmetric image in Fig. 4 has 2.04% of the energy in the raw image.

The remaining step is to find the 4 symmetry components in the x-y plane. These symmetry components have even-even, odd- odd, even-odd and odd-even symmetry and may be found by simply flipping the asymmetric image above 3 times and averaging it with the original image [2]. Since this process has been described elsewhere, we simply show the 4 components for this image in Fig. 5 along with their energies.

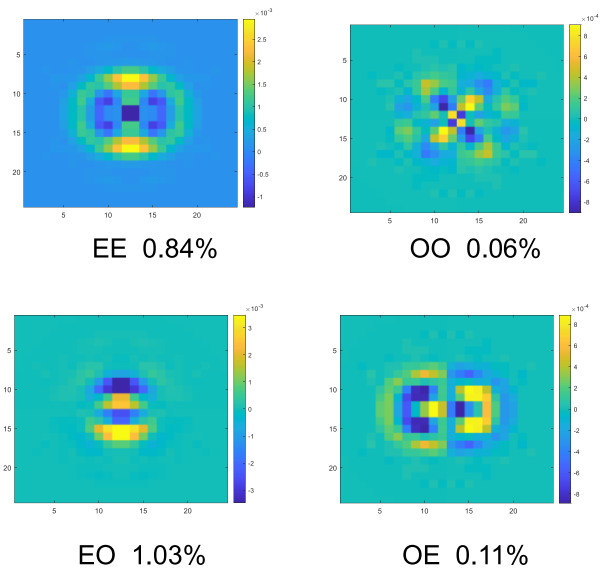

FIGURE 5. The asymmetric components EE, OO, EO and OE of the image in FIGURE 4 along with the percent of the total raw image energy in the component.

The 4 symmetry components in the x-y plane are clearly obvious in Fig. 5, but what does this have to do with mechanical degrees of freedom? Going back to the original question of aligning an OAP, Fig 6 shows the situation. If the OAP is translated in X, it only affects focus because that direction is along the axis of the microscope and the collimated beam remains normal to the flat. If the OAP is translated in either Y or Z, the reflected image moves laterally away from the focus projected by the PSM. The only way to keep the image centered is to make a compensating rotation about Z centered on the OAP. For a Y translation a about Y for a Z translation is needed. (Because the OAP is off axis, a rotation about X will also shift the image in Y. If the rotation is about Z located at the optical axis nothing happens.)

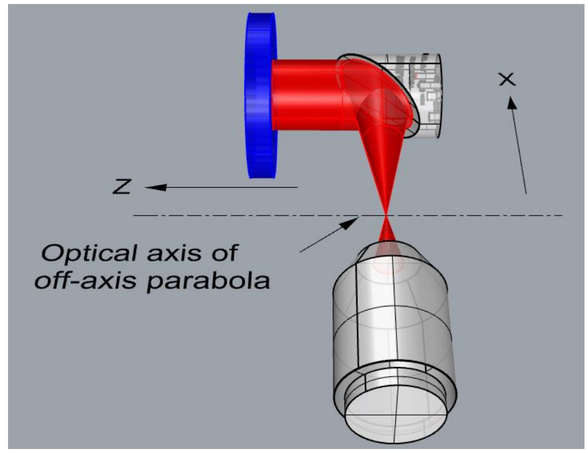

FIGURE 6. The OAP of FIGURE 1 with axes identified for the explanation in the text.

USING SYMMETRY FOR ALIGNMENT

Going back to the asymmetric parts of the image, a translation in Y of the OAP from being well aligned introduces OO and EO components while a translation in Z introduces EE and OE components. In practice, the easiest method of alignment is to use the Y translation and Z rotation to minimize the OO and EO components, and then concentrate on the EE and OE components. Invariably, working on the EE component will slightly misadjust the OO and this adjustment must be touched up, and then the EE again. Final alignment is accomplished when the symmetric component is as large as possible and the asymmetric parts are smallest.

MID-SPATIAL FREQUENCY ERRORS

Aside from alignment, the asymmetric components have information about the overall roughness of the surface. If this technique is simulated in a lens design program to introduce a small misalignment there are still asymmetrical image components but they are smoothly varying, nothing like the variation in Fig. 4. I have not had a chance to study this effect, but it is like the images I have seen from surfaces that have mid-spatial frequency roughness. I believe that by taking a series of raw images as the PSM is moved through focus and analyzing the asymmetric images a power spectrum of the surface roughness can be found. As an example, Fig. 7 is a series of OO grayscale images as the microscope is moved through focus in 5 μm steps. Clearly the symmetry method is gathering systematically useful information. It is now time for further study.

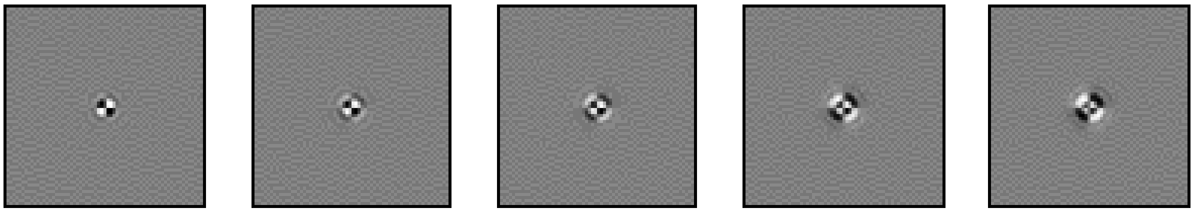

Figure 7. The OO component images of the raw image in Figure 3 as the microscope was stepped through focus in 5 μm steps from best focus (left)

CONCLUSION

Most optical systems must be aligned in 5 degrees of freedom while stigmatic images contain 5 symmetry components. We have shown that in most cases there is a one-to-one correspondence between the image symmetry components and the 5 DOF adjustments that affect image quality. This correspondence leads to a systematic approach to the alignment of optical systems using the image symmetry components. These components are easy to calculate and can be displayed at frame rates of 20 to 30 Hz. This provides real time feedback for making manual adjustments and offers promise for making automated adjustments.

In addition, the pattern within the symmetry components seems to offer insight into the mid-spatial frequency roughness of the optics being aligned.

ACKNOWLEDGEMENT

The help of Dr. Kashmira Nakhoda of RayKi Consulting and Brian Brondel of Astronomical Consultants & Equipment, Inc. with the software used in preparation of this paper is gratefully acknowledged.

REFERENCES

[1] https://www.opticalperspectives.com/product/point-source-microscope

[2] Parks, R. E., "Using image symmetries to uniquely align aspheric mirrors to a focus and axis", Proc. SPIE, 12222, pp. 24-32 (2022).