Systematic method of optical alignment using aberrations

Robert E. Parks[*a], Benjamin F. Anjakos[b]
[a]Optical Perspectives Group, LLC, Tucson, AZ 85750
[b]Steward Observatory, The University of Arizona, Tucson, AZ 85721

ABSTRACT

We use a known optic, a catalog off-axis parabola, as a reference to both model in Zemax and to align while tracking the position of the focus in 3 degrees of freedom (DOF) and the tilt of the auto-reflecting flat in 2 DOF to demonstrate a systematic approach to alignment. The aberrations present at each step of the experimental procedure are monitored using an autostigmatic microscope.
Keywords: Optical alignment, off-axis parabola, autostigmatic microscope

1. INTRODUCTION

There is nothing new in this paper, but rather it is a series of observations made of many years of doing alignment. Most of these observations are obvious but at the time you are in the middle of aligning some, usually expensive, optic and under time pressure you tend to forget the obvious and only get more frustrated as the alignment seems to get worse instead of better no matter how hard you work. Thus the purpose of this paper is to provide suggestions of approaches to follow at various stages of the alignment, and the reasons for the suggestions. As with all optics, no solution fits all cases, and the devil is in the details. Hopefully, these suggestions help you get to a satisfactory alignment a little faster.

In the sections below we will go into more detail. These suggestions are meant to apply to any alignment tool but we prefer using an autostigmatic microscope in a double pass configuration. Either an alignment telescope or an interferometer will also work. The general flow of the alignment will follow this pattern:

- Set the optical axis of the alignment instrument
- Assure that the mountings of all components have the necessary degrees of freedom and range of adjustment
- For all components that focus or have centers of curvature, get them as close as possible to their nominal mechanical positions as possible using mechanical means
- Use a low power objective or transmission sphere initially
- Keep the double pass return mirror as close as possible to the asphere being aligned
- Adjust the point source of light incident on the asphere to give a nominally collimated beam that is as symmetrical as possible by eye
- Adjust the return mirror to get the reflected, focused spot into the objective or transmission sphere
- Continue centering the spot on the alignment sensor so it is on the crosshair or there are few tilt fringes in an interferometer and the spot is as well focused, that is, as small as possible
- For final alignment, keep spot centered while making compensating tilt and decenter adjustments until no improvement is made in wavefront error or spot size and symmetry

Before getting into the alignment steps, it had been our intention in this paper to share our observations about using new AI software[1,2] to obtain Zernike coefficients as a way of guiding alignment. The software was originally developed for use with aligning astronomical telescopes. We found that there were enough differences between that use and using the software with an ASM for alignment that it was not a practical approach right at the moment. The software works well for finding Zernike coefficients using the Point Source Microscope[3] but not in a mode compatible with simultaneously doing alignment.[4] We probably have enough material to write another paper describing the difference between the astronomical application and this one for alignment using an ASM.

* reparks@opticalperspectives.com; phone 1 520 529 2950; optiper.com

2. ALIGNMENT STEPS

2.1 Set the optical axis of the alignment instrument

In this first step you are boresighting your instrument. With an autostigmatic microscope (ASM) you focus on a specular surface and set the crosshair on the reflected focused spot, the Cat's eye reflection. Similarly with an autocollimator and objective. Center the origin of the instrument on the Cat's eye image. With an interferometer you do the same thing to get a Cat's eye reflection and adjust the transmission sphere for as few fringes as possible, that is, no tilt. Then you know that when a reflected spot comes back in your alignment setup and it is centered on the crosshair, or there are little to no tilt fringes, the light is returning to the instrument over the same path that it left. This means there will be no retrace error contributing to your alignment.

2.2 Assure you have the necessary adjustments and range of adjustment

Here I want to distinguish between what I call hard and soft alignment adjustments. With a plane mirror, it defines 2 degrees of freedom (DOF) in angle that are hard, or critical, adjustments that may be important down to a second of arc, possibly better. Then there are 2 translational DOF that are needed to make sure the entire beam falls on the face of the mirror. These are soft adjustments that if made to a mm or so are just fine. If the beam is not well centered, it is aesthetically unpleasing but does not impair the alignment. Similarly, with the ASM or interferometer (INT) you have 3 translational DOF that are critical because for either instrument the light comes to a focus defined by 3 DOF. These DOF are hard because by being off even a few µm leads to many fringes of tilt or focus. The direction either instrument points is a soft alignment and being off a few degrees in angle will not affect the results of the alignment you are trying to perform.

Further, alignment is paraxial. You do not need to fill the whole system aperture as you do if you are measuring wavefront error. If you believe you have a mirror that is good to $\lambda/4$ over the whole aperture it is surely going to be $\lambda/4$ or better over a subaperture. The place where pointing an alignment instrument may cause a problem is if the beam is too close to an edge where there is a roll off in figure error. This may be interpreted as an alignment error rather than being an error in the mirror.

Lastly, in this section, when setting up the hardware try to set all the adjustment screws mid range. If you start out toward the limit of adjustment in one direction, Murphy's Law says that is the direction you will need more adjustment. Murphy is sure to catch up with you somewhere along the alignment process in any case.

2.3 Set all components with critical adjustments as close as possible to their nominal positions

Start by getting all components to the same height off your optical table. Use the component least adjustable in height as your reference. For example, interferometers are difficult to adjust in height and certainly cannot be made shorter. From here use the tapped holes or a straight edge to help get the components close to nominal positions looking down on your setup. A plastic ruler is a big help here as it will cause less damage than a metal one. The straight edge or table holes help with getting angles correct. Do not be afraid to mark on the table with a Sharpie. The mark will come right off with a little alcohol.

2.4 Use a low power objective or slow transmission sphere.

Just as in using a microscope, you start with a low power objective to find the object you want to examine and then switch to higher power objectives once you find the object, start your alignment with a low power objective to make it easier to get the light back in the objective to begin with. Using an INT is harder because transmission spheres are not parfocal and you do not want to move your INT once you get your setup initially aligned. Best to use the transmission sphere you intend to use in the end and stop it down with a mask centered on the aperture. This goes back to the concept that alignment is paraxial and you do not need to fill the full aperture in the case of hard alignment where you are using centers of curvature.

If you are aligning using aberrations, yes, you do need to fill the aperture so you take into account any figure error in the optics themselves as a part of the alignment. However, when you are still at the stage of initial alignment and just trying to get light back in your alignment sensor, anything you can do to de-sensitize your setup initially helps. Once you have captured the double pass reflected light you open up to the full aperture of the system or install a higher power objective so you completely fill the system under test.

2.5 Keep the return flat close to the asphere being aligned

Assuming the system being aligned produces a collimated output you can theoretically place the plane return mirror any distance for the system. However, initially keep as close as practical to minimize the optical path so when the light path is at an angle to what it should be in the aligned system the lateral shift of the beam is minimized on its return path. Once the system is aligned the plane mirror may be moved back, but it is still a good idea to keep the total optical path as short as possible. Increases in the air path only hurt you in terms of environmental noise both from air turbulence and vibration.

(Sidebar – As you set various mounts on the optical table, remember that nothing is truly flat. If mounts are screwed down to the table you are generally safe. But if you have to stack one component on another and the interface is slightly convex or close but not quite kinematic, the interface is likely to oscillate. It is much better to assume the mating parts are not flat and put thin tape at 3 locations roughly 120 degrees apart at the edges of the interface so there is a definite kinematic interface. This is particularly true for interferometric setups. Fringes that oscillate wildly are no use when it come time to take data. Better to think ahead and correct the potential problem ahead of time rather than have to tear it down to fix the problem later.)

If you are aligning a finite conjugate system you do not have this option, the powered return mirror must be at the proper distance from the system. Here the only way to desensitize the setup is to stop it down. Tests for ellipsoids and hyperboloids fall in this class of test. The spherical return mirror must be at the design conjugate to get the light back focused at the correct distance.

2.6 Adjustment of the finite source relative to the first surface

This initial adjustment may take many forms, but if, for example, you are aligning a parabola then the light reflecting from the parabola should appear roughly collimated and the beam roughly symmetrical. If you are filling the whole aperture you may not have enough light to see this but if a narrow cone of light from the source can be projected toward the parabola, the reflected beam may be bright enough to get an idea of the collimation and symmetry. If the beam does not appear collimated then it is obvious that the source must be moved toward or away from the parabola. Similarly for other situations.

If the reflected beam lacks symmetry then the misalignment is lateral and that is the sort of adjustment that should be made. All this may seem obvious as you read but in the lab the tendency is to put all the components in place in nearly as possible mechanically and then turn on the light source. Unless you are extremely lucky the return beam is nowhere to be found and if you start looking near the return focus you are likely to be out of luck. By checking for approximate optical alignment as each component is inserted in the train the more likely the return beam will be near the input conjugate.

While I said above to place components as nearly as possible where they are supposed to be mechanically according to the design, it is very helpful to also check optically that the beam is going where it is expected and that it have approximately the symmetry expected. Also, this is a good time to check on the “soft” alignment aspect of the setup. Is the light centered on each aperture, not exactly but roughly by eye. In this day of the laser we never want for photons. The end of a single mode fiber is a perfect temporary point source of a 0.1 NA cone of light. If this beam makes it through your setup and back approximately correctly you can then substitute your alignment instrument that may have a less intense source. (None of the above means ignoring proper laser safety. But if you need more photons for alignment they are easy to get in most cases.)

2.7 Adjust the return mirror to follow the beam back

Once the light beam reaches the return mirror and still appears roughly collimated and symmetrical follow the beam back. If the return mirror is aluminized (in general, it should be) the return beam will be nearly the same intensity as the incoming and it will be relatively easy to follow the edges of the beam back so you can see that the reflected beam stays on top of the incident.

At this stage in the alignment it is handy to have an aid to find the reflected focused image. A white business card works well by inserting it into the focused outgoing beam, then withdrawing it just enough so the outgoing beam is not blocked. By inserting the card on all 4 sides of the outgoing beam you can find the reflected focused beam if you are close to the correct focus. Even if you are somewhat away from focus just knowing where the tightly focused return beam is helps with the next adjustment which is focus, to make the outgoing and return focus in the same plane. Then adjust the return mirror to get the light back into the objective.

Another useful guide is to use matte finish Mylar in which you punch a small hole, perhaps 3 mm in diameter. Then the outgoing focused beam can pass through the hole unobstructed, and the matte finish scatters the return focused light making it visible. Then you must get the return light back through the hole at which point it should be going into the objective, or very close to it.

This step is analogous to aligning a plane mirror to an autocollimator. It is easy if the plane mirror is close to the autocollimator because of the relatively large autocollimator aperture. As long as some reflected light makes it back into the objective you have a light pattern to guide you to precise centration. If the mirror is at the other end of a long lens bench alignment is more difficult because a small angular error means the reflected beam is far from the autocollimator aperture. This is when you dim the room lights and shine a flashlight into the autocollimator eyepiece in hopes that the reflected beam is bright enough to show up on a white piece of paper so you can guide the beam into the autocollimator aperture.

With an autocollimator you are only aligning the beam in 2 degrees of freedom (DOF). With a finite conjugate system using an ASM or autocollimator with an auxiliary focusing objective you now are searching for the return reflection in 3 DOF and you do not have to be far out of focus before there is insufficient light to see the return beam unless your card is very close to focus. This is a major practical reason that ASM were not practical instruments for general use before the advent of the laser. Unless you had a good idea of where the reflected image would be, as you did measuring test plate radii in an optics shop, the autostigmatic microscope was frustrating at a minimum and useless otherwise.

2.8 Center the image on the crosshair

Once the reflected light enters the objective it is easy to center the image on the crosshair. The image will be aberrated, that is, large and asymmetrical due to the remaining misalignment, but now you can begin to make the small adjustments to bring the system into full alignment. You want to keep the image centered on the crosshair and in as good focus as possible. Keeping the image centered and in focus means you have got the system aligned in 3 DOF, and that the light is incident on the return mirror at normal incident aside from the small errors due to the residual aberrations from misalignment. Now the quantitative systematic part of the alignment begins.

If you are using an INT, the same comments apply, it is that you keep the tilt to a minimum as you do the remainder of the alignment. When using a small sensor like an ASM it is easy to move the ASM in 3 DOF and the return mirror in 2 angular DOF. Interferometers are difficult to move so you either must move the component you are aligning in 5 DOF, or the component in 3 DOF and the return mirror in 2 DOF. This is the main difference between using an INT to align a setup or an ASM.

If it is necessary to use an INT because there is a requirement for interferometric data, it is still often easier to do the alignment as well as possible with an ASM and then bring the setup including the return mirror to the INT, or bring the INT to the aligned setup. In either case, the “hard” alignment to the INT is in only 3 DOF since the focus of the transmission sphere is a point. If the INT is aligned to a degree or 2 in angle will have no effect on the final data as long as the angular misalignment does not clip the aperture of the item under test.

3. SIMULATION OF ALIGNING A 90° OFF-AXIS PARABOLA TO A RETURN FLAT

Now that we have reached the point where light is detected in the objective or transmission sphere, we begin the formal systematic approach to alignment. The model uses a Thorlabs MPD129, 1” diameter, 90° off-axis parabola

(OAP) because we can get real data from the same hardware. With a 4x objective on our ASM, a Point Source Microscope, a typical alignment situation might have the return mirror tilted away from the axis of the OAP by -0.7° about the x axis and -0.5° about y as in Fig.1. Figure 2 shows the actual hardware.

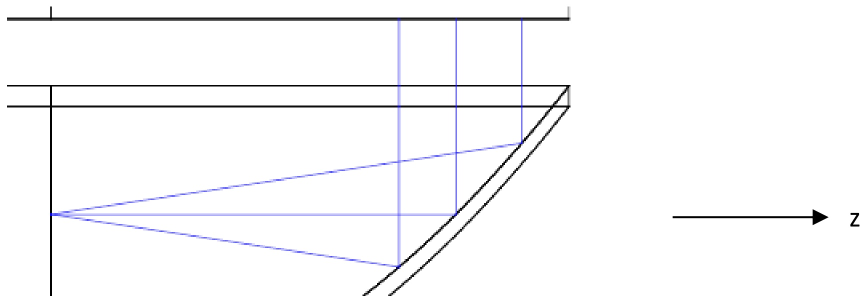


Figure 1. Optical layour of the 90° off-axis parabola and plane return mirror used in the example.

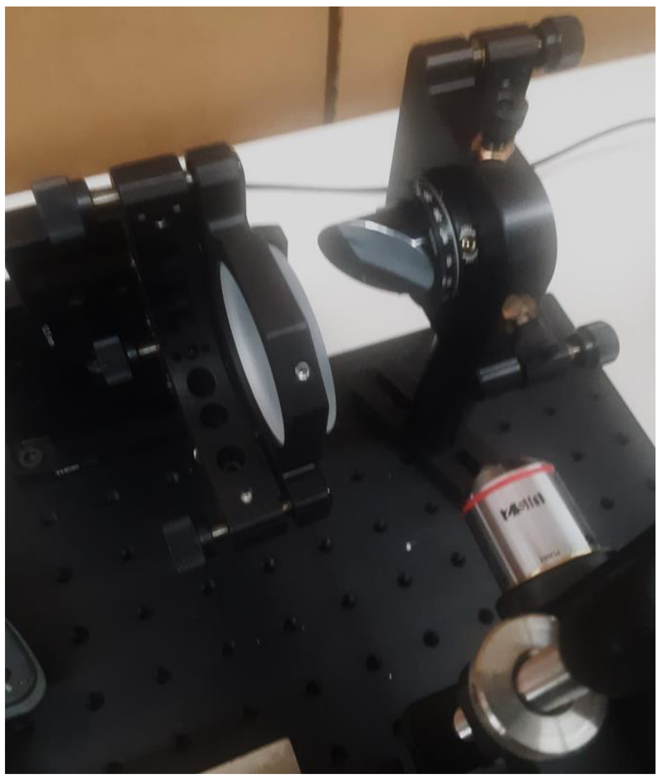
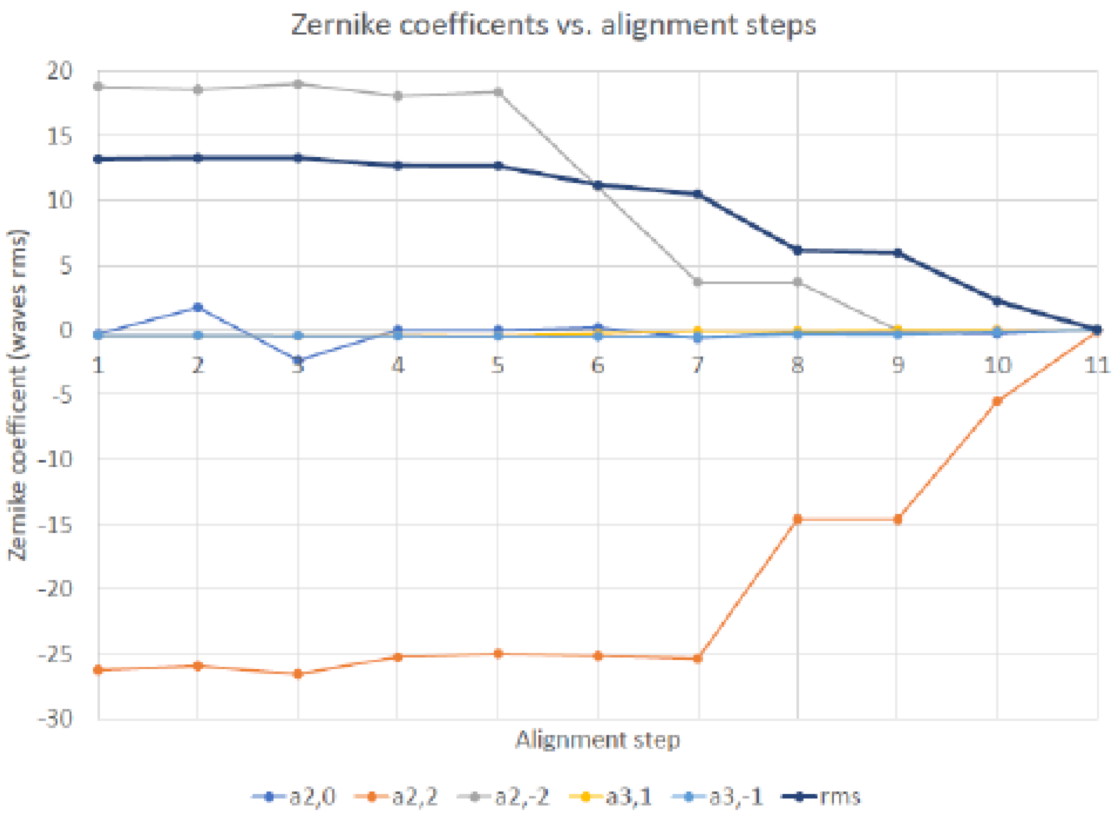


Figure. 2. Hardware used in the example with the OAP in the upper right corner and the 4x objective mounted on a PSM extending out of the Figure to the lower right.

3.1 Step 1

In Fig. 3, spot diagrams and the table show the improvement in wavefront error for each alignment step. Step 1 shows the conditions initialy where light is first seen in the objective. The graph shows an overall view of the alignment while the table shows the specific numerical values for each step and the particular adjustment made at each step (highlighted). At first, and throughout, astigmatism dominates the alignment errors because the OAP is so far off axis. If the parabola was symmetric, or only slightly off-axis coma would have been the main error.

The spot diagrams show that effect of alignment on the image size and shape. The numbers 1000, 400, 100 and 10 refer to the scale of the spot graph extent in um. It is clear not much happens to the spot size until step 8 even though the spot is roughly round and it looks like the error is mostly defocus. In fact, the large spot size is due to the



Alignment step	1	2	3	4	5	6	7	8	9	10	11
a2,0	-0.29	1.75	-2.35	0	0	0.2	-0.61	-0.21	-0.2	-0.27	0.013
a2,2	-26.25	-25.94	-26.55	-25.26	-25	-25.16	-25.39	-14.59	-14.6	-5.5	-0.099
a2,-2	18.79	18.57	19	18.06	18.38	11.03	3.7	3.69	0	0	0
a3,1	-0.45	-0.44	-0.46	-0.43	-0.45	-0.27	-0.09	-0.09	0	0	0
a3,-1	-0.43	-0.42	-0.45	-0.46	-0.47	-0.5	-0.52	-0.32	-0.33	-0.13	-0.001
rms	13.2	13.3	13.3	12.7	12.69	11.23	10.48	6.14	5.96	2.24	0.041
Image x (mm)	-0.893	-0.893	-0.893	-0.893	0	0	0	0	0	0	0
Image y (mm)	-1.251	-1.251	-1.251	0.001	0.004	0.001	0.001	0	0	0	0
Sensor x (mm)	0	0	0	0	0.446	0.286	0.089	0.089	0	0	0.003
Sensor y (mm)	0	0	0	0.621	0.621	0.621	0.621	0.355	0.355	0.134	0
Flat α (deg)	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.4	-0.4	-0.15	0
Flat β (deg)	-0.5	-0.5	-0.5	-0.05	-0.5	-0.3	-0.1	-0.1	0	0	0.002
Focus (mm)	0	0.1	-0.1	0	0	0	0	0	0	0	0

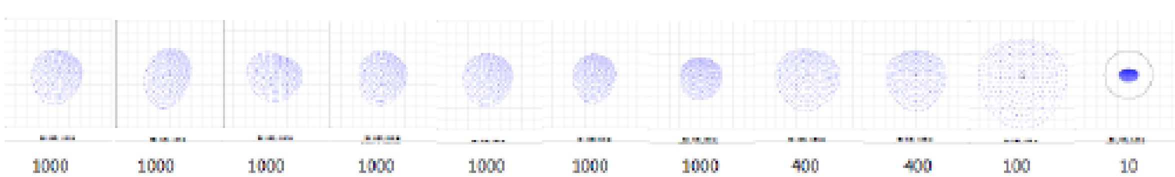


Figure 3. Change in Zernike coefficients with alignment step (upper), numerical values of Zernike coefficients, image positions and hardware locations (middle), and simulated spot diagrams with overall scale in μm (lower).

astigmatism at best focus, and this is the minimum spot size at the “circle of least confusion” of the astigmatism. The spot does not get significantly smaller until the astigmatism is reduced.

The table shows the 11 alignment steps, then the 5 3rd order Zernike coefficents affected by alignment, namely, focus astigmatism and coma. Under this is the rms wave error at each step. This is followed by the image position in the ASM field of view, the ASM location in space and the tilt of the plane return mirror relative to normal with the OAP axis. Focus is a z position of the ASM.

Notice there are 5 adjustment that affect alignment, 3 translational DOF of the ASM and 2 angular DOF of the flat. These 5 DOF exactly match the significant optical wavefront errors caused by misalignment. Further, the 5 wavefront errors have the only 5 possible symmetries; focus being rotationally symmetric, astigmatism having even-even or odd-odd symmetry and coma having even-odd or odd-even symmetry.

3.2 Steps 2 and 3

In steps 2 and 3 the ASM was moved ± 0.1 mm in z to see whether the ASM was well focused and to see how the signs or values of the focus and astigmatism terms varied with focus. With a positive ASM motion, that is moved away from the OAP (or in the -z direction), the Zernike focus coefficient gets more positive while the a2,2 (even-even astigmatism) gets more positive and the a2,-2 (odd-odd astigmatism) gets less positive. These behaviors help determine which direction an adjustment should be made and whether the observed image behavior gets better or worse.

At this first stage of alignment when light is initially captured by the objective, it is sometimes difficult to detect whether adjustments are being made in the right direction to improve alignment. You can see from Steps 2 and 3 that the overall shape of the spot diagram rotates about 90 degrees as you go from one side of best focus to the other. If you go farther out of focus to where the astigmatism forms a line with a minimum width and note the amount the ASM was moved, and then shift to a similar condition on the other side of focus, where the line has rotated 90°, the alignment is getting better if the focus shift of the ASM is decreasing between alignment steps. Simply looking at the image may not be a good indicator of improvement, but a decrease in the focus shift between the 2 orientations of astigmatism is a definite sign that the alignment is improving. Also, as you go farther from best focus the image gets dimmer.

3.3 Step 4 through 7

In step 4 the ASM was moved +0.621 mm in y to center the reflected spot on the crosshair. This made a slight improvement in the rms as a hint this was the right direction to move. Step 5 was the same but centering the spot on the crosshair in x by moving the ASM +0.446 mm. In Step 6 the flat was rotated +0.2° about the z zxis and the ASM moved in y back to 0.286 to keep the image centered in the ASM. This made a noticable change in the a2,-2 coefficient and slight improvement in the rms. Since this was going in the right direction another 0.2° tilt was made in Step 7 again improving a2,-2 by a proportional amount.

3.4 Step 8

While the a2,-2 astigmatism was improving the rms and spot size were only making modest improvement so in Step 8 the flat was tilted 0.3° about the x axis and the ASM moved to 0.355 in y for a substantial improvement in a2,2. What may be confusing about the directions and axes is that when looking along the z axis toward the OAP, the x direction on the ASM image monitor and the motion of the ASM is in the y direction of Fig. 1. The y image and ASM motion are in the x direction of the Fig. 1. It all makes sense when you look at the real hardware from behind the ASM.

3.5 Steps 9 through 11

In Step 9 the remainig tilt in the flat about the x axis was removed and the a2,-2 astigmatism term dropped to zero although the spot size was largely unchanged. It was only in Step 10 when most of the remaining tilt about z axis was removed was there a substantial improvement in spot size and reduction in the rms wavefront error. Note the change in scale in the spot size plots and that they remain fairly round that make it look like focus error where it is actually astigmatism. Only in Step 11 where all but about 7 seconds of arch tilt were left in the flat did the geometrical image drop below the diffraction limit. Notice that in every step of the alignment the image was kept centered on the ASM crosshair by compensating tilts of the flat and translation of the ASM while keeping the image well focused.

Even at this stage of alignment it is clear the alignment is not perfect because by going out of focus just 6 µm either side of focus you see the a2,2 astigmatism meaning there is not perfect alignment in the plane of the page. Also notice that the a2,-2 or 45° astigmatism is associated with alignment out of the page while the a2,2 astigmatism is related to alignment in the plane of the page. This is why in a paper from over 40 years ago I suggested that off axis conics be aligned by first aligning the astigmatism with the x-y axes and then finish the alignment with adjustments along the x axis. I did not understand the reason then but this example shows the reason why.

Another misconception about astigmatism is that it rotates as you go through focus. It appears to rotate but the astigmatism coefficient is not what changes, it is focus. The astigmatism appears to rotate because of the way it interacts with focus. This was the reason for checking the magnitude change in astigmatism as we went through focus in the early part of the alignment. You want to know which direction to move to reduce the astigmatism.

4. DATA FROM IMAGES DURING ALIGNMENT

4.1 First impressions from images

Fig. 4 is the reflected image from the OAP in the experiment after it was reasonably well aligned but with the intensity of the source increased to definite saturation of the detector for the core image. In addition to the roughly symmetric pattern of brighter pixels in the image due to scattered light from the surface and the ASM itself, there is a horizontal band of scattered light that make it obviouss this is a diamond turned surface. Any time there is a linear band of scattered light is is clear there is a linear grating structure of some sort on the surface under test. Even a structure with a height of no more than a nanometer will produce this sort of scattering if the source intensity is bright enough. Further, the grating structure does not have to be uniformly spaced lines, simply a pattern when the lines of the structure are roughly parallel will produce this type of scattering. While this is undesirable, the effect of the pattern can be used as an aid to alignment.

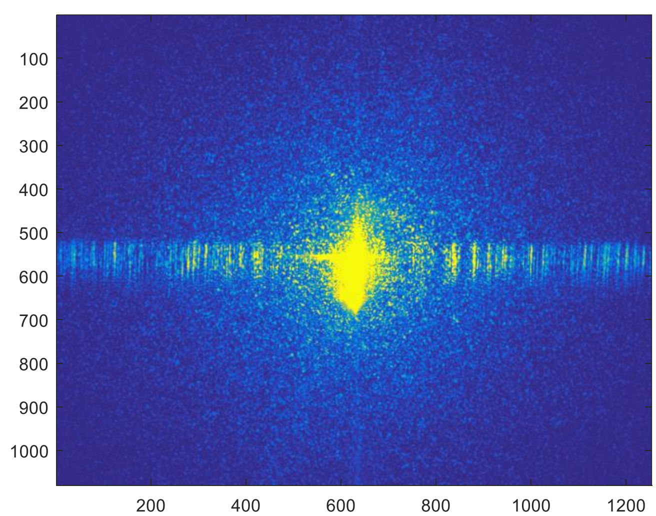


Figure 4. Overexposed picture of the reflected focused image from the diamond turned OAP used in the experiment showing the linear scattering that inicateds a grating structure on the surface.

4.2 Images through focus divided into symmetry groups

Once the light was in the objective and close to best alignment a series of images was taken about every 3 µm in focus to determine best focus and what alignment remained to be done. The images are shown in Fig. 5.

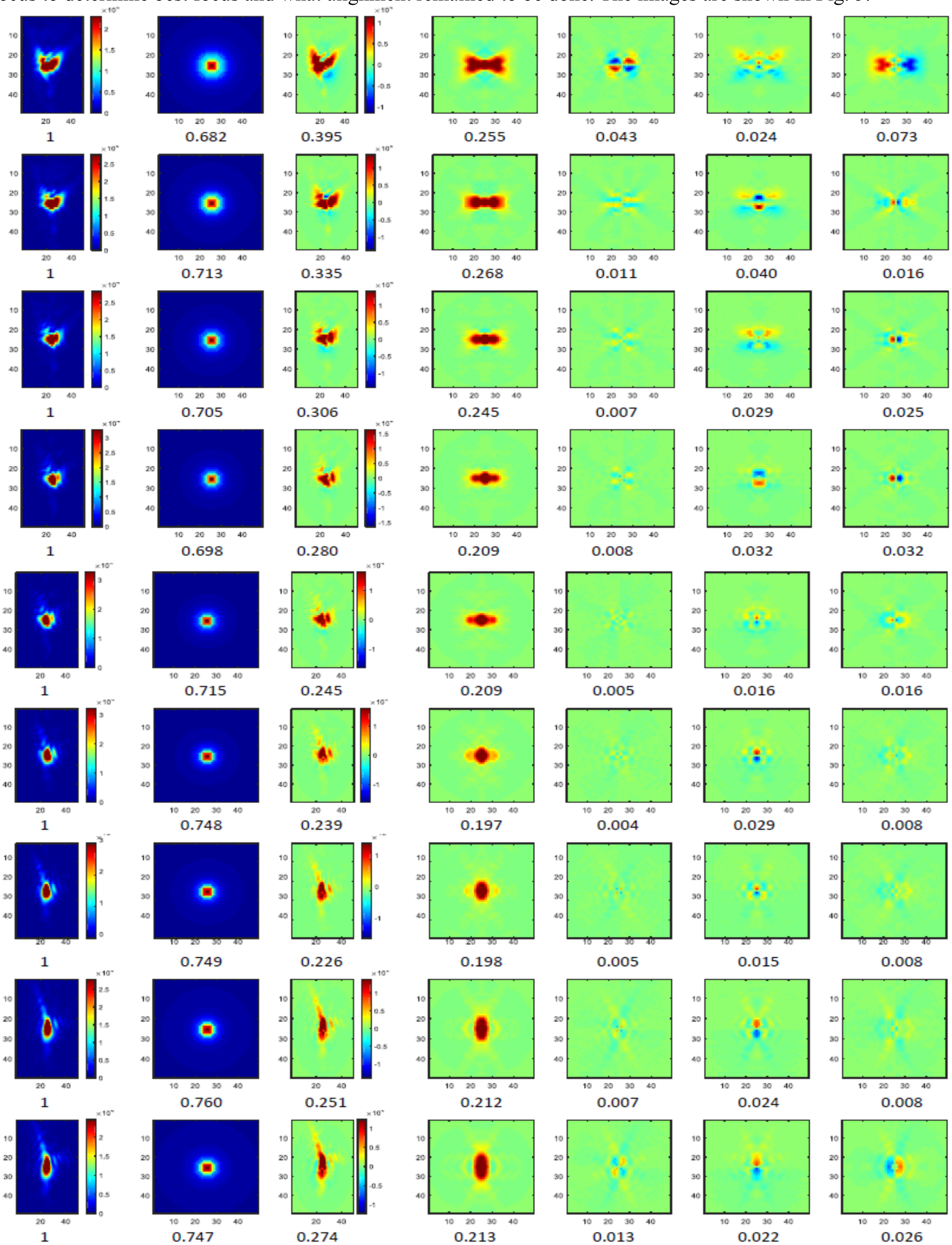


Figure 5. Through focus decomposition of the reflected image into 5 symmetry moving through focus (vertical direction) Left to right the raw image and its rotationally symmetric portion.with 0 to 3.3 color bar, then the asymmetric portion with colorbar of ± 1.65 and the EE, OO, EO and OE parts with the same colorbar. Numbers are relative parts of image.

In Fig. 5 the 7 horizontal colormaps represent the symmetry portions of the image while the 9 horizontal rows are through focus positions 3 µm apart. The left most map is the raw image normalized to 1 and a color bar running from 0 to 3.3. (The map should be square but the colorbar squeezed the map.). The next is the rotationally symmetric part of the image, the part we are trying the maximize by alignment.

The 3rd image is the asymmetric part of the image obtained by subtracting the symmetric part from the raw image. Because this crates negative values the maps are renormalized to ± 1.65 keeping the same intensity range for easy comparison. The asymmetric image is then broken down into even-even, odd-odd, even-odd and odd-even parts by the method previously described[5]. The numbers represent the relative proportions of the image in each symmetry group when the raw image intensities are normalized, or set equal to each other.

Before going into the meanings of the numbers going through focus, I should comment on the raw image itself. This is a diamond turned mirror and we saw the effect of the grating structure in Fig. 4. The raw image is rather irregular and this irregularity shows through in the asymmetric parts of the image. The irregularities are due to mid-spatial frequency errors in the surface. This is another advantage of looking directly at the image. It contains easily recognizable features of an optical surface or system in addition to just the aberrations.

4.3 Analysis of the images through focus

An easy way to see how the image changes as we go through focus is to plot the symmetry group numbers versus defocus as in Fig. 6.

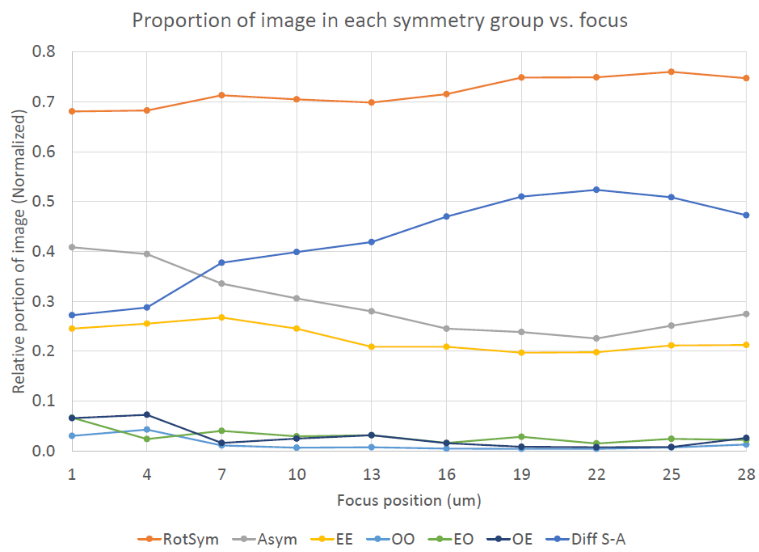


Figure 6. Proportion of each symmetry group in the raw image and the difference between the rotationally and the non-rotationally symmetric errors

As the ASM was moved through focus there was a modest increase in the rotationally symmetric error but the significant change was a decrease in the asymmetric errors. The difference curve shows the best focus was at 22 µm although this might not have been the conclusion simply looking at the images in Fig. 5. The other obvious feature of this graph is that the parabola is not fully aligned as there is significant intensity left in the EE part of the image implying the there should be further alignment in the x axis. As would be expected there is little coma type error and the alignment is good in the y axis as shown by the low values of the OO error. The EO and OE symmetries are good at showing the mid-spatial frequency errors particularly on either side of best focus. You see the same behavior with an INT by looking at the low order Zernike coefficients.

5. CONCLUSIONS

We have given suggestions for setting up a test of an aspheric mirror in double pass autocollimation where either an ASM or an INT is used as the test instrument. Because it is the test of an asphere there are 5 degrees of freedom to align correctly as opposed to the 3 degrees of freedom in the test of a spherical mirror. This makes it even more important to position the elements of the test correctly using mechanical measurements prior to doing any optical alignment.

Once optical alignment is begun, it is best to use a low NA beam for initial alignment because the slow beam is less sensitive to the effects of aberrations that tend to confuse the operator during the initial phases of alignment. Even after getting light back into the test instrument a low NA cone of light makes it easier to decide which adjustment to use and which way to make the adjustment to improve alignment. The ability to move back and forth through the apparent best focus is also helpful.

When light is getting to the test instrument the first order of alignment is to center the aberrated spot on the crosshairs of the ASM or to remove as much tilt as possible from the fringe pattern with an INT. Then compensating tilt and decenter adjustments are made while keeping the image centered on the crosshairs and in as good focus as possible. Another tip as to the correct direction of adjustment is that if the image intensity is getting dimmer you are going farther from best focus because the energy in the spot is spread out over more space.

For the final alignment adjustments, it is useful to have quantitative indications of the symmetry of the image or low order aberrations. Since there are only 5 useful degrees of freedom for optical alignment it is only necessary to be concerned about the lowest order aberrations or symmetries. Best alignment is obtained when as much energy as possible is in the rotational symmetric part of the image and the least in the asymmetric part. The is no way to align out higher order aberrations. Also, if the asphere has a low order aberration built into its optical surface, this approach to minimizing the asymmetric errors compensates for the error in the optic with alignment to give the best concentration of energy in the rotationally symmetric part.

We regret that we were not able to demonstrate the use of the AI software in this paper. There were too many differences between its original use and use with the PSM to work in this demonstration. However, the software does work to make the PSM a wavefront sensor[4]. It was just not practical at this time to demonstrate this capability until the AI portion can be fully integrated with the original PSM software.

6. REFERENCES

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