The autostigmatic microscope and the origins of the Point Source Microscope (PSM)

When most people envision a microscope, they typically picture one that operates in transmission, with the light source beneath the sample and the microscope objective and eyepiece above. However, an autostigmatic microscope (ASM) stands out from this model. It functions in reflection, like an autocollimator or interferometer. The light source is housed in the microscope body and is introduced by a beamsplitter positioned close to the objective but between the objective and eyepiece, as depicted in Fig. 1. Notice that if the microscope objective were replaced by an infinite conjugate objective, the instrument would be an autocollimator.

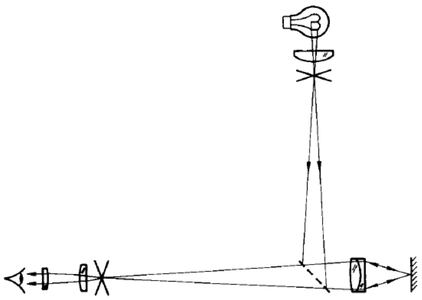

Fig. 1 An autostigmatic microscope (from Steel[1])

An ordinary reflecting microscope, such as one used to examine opaque samples, uses an extended light source that is imaged on the entrance pupil of the objective so that the light is made to uniformly flood the sample over the microscope field of view. An autostigmatic microscope is different in this respect in that a crosshair or pinhole source of light is placed conjugate, via the beamsplitter, to the eyepiece object plane. This means that an image of the crosshair or pinhole will be in focus at the focus of the microscope objective. In some very simple cases, the coiled filament of the light bulb making up the source is conjugate to the eyepiece object place so that when the microscope is focused on a surface the filament is in good focus viewed through the eyepiece.

This detailed explanation of an ASM is crucial because they are a fundamental tool in nearly every optics shop despite the scarcity of literature references to them. Their primary use is in measuring test plate, or lens surface, radii of curvature. The only literature reference I have come across is a paper by W. H. Steel titled “The Autostigmatic Microscope,” which cites a reference to C. V. Drysdale in 1900 in the Transactions of the Optical Society of London. Mr. Drysdale started the Technical Optics Department at Northampton Institute in that same year, underscoring the fact that ASMs have been in existence for over a century.

Going back to Steel’s paper describing an ASM, it was probably written for the same reason as this paper: his audience had very little idea what an ASM was and what it was used for. His audience happened to be optometrists because he was working at CSIRO, the Australian version of NIST in the US, with a task to measure the radii of curvature of contact lenses back in 1983. In the paper's abstract, he stated, “The autostigmatic microscope is an instrument for measuring the line-of-sight distance to a reflecting surface and is used chiefly to measure the radii of lens surfaces.” He says the ASM is an analog of an autocollimator that focuses at a finite distance rather than infinity.

The only other place I have seen an ASM mentioned is in Warren Smith’s book *Modern Optical Engineering* toward the very end, where he calls it an autocollimating microscope[2] and describes its use the same Steel. The implication in Malacara's *Optical Shop Testing*[3] is that one would obviously use an ASM in many cases of optical testing, but ASMs are never mentioned explicitly.

How the ASM works

Before going further, we should explain how the ASM works in the two modes used to measure radii. The principles are most easily explained by considering the light source as a pinhole conjugate with the object plane of the eyepiece. In this case, an image of the pinhole will appear at the objective focus and be smaller than the pinhole source by the magnification of the objective. If the pinhole source was 50 µm in diameter, it would appear as 5 µm in diameter at the focus of a 10x objective. Also note, as in Fig. 1, microscopes in the time frame of Steel's paper used finite conjugate objectives, so the objective was the only optical element with power in the microscope. This is a perfect example of a stigmatic optical system, one that images a point of light in the object plane into a perfect point in the image plane.[4]

If the ASM were focused on a specular surface, as in Fig. 2, the light coming from the top part of the objective aperture would reflect off the surface and re-enter the objective at the bottom of its aperture, and vice versa. This is the so-called Cat's eye, or retroreflection, focus. Notice that the surface does not have to be normal to the optical axis of the objective. The reflected light will always return to the pinhole source on the other side of the axis from which it started out. The reflecting surface can be tilted from normal until none of the reflected light makes its way back into the objective, but whatever light does make it into the objective will always focus back on the source pinhole.

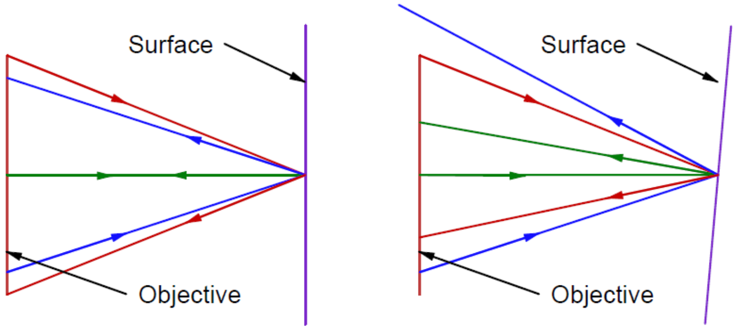

Fig. 2 Cat's eye reflection with the surface normal to the optical axis of objective (left) and with the surface tilted (right)

Due to this retroreflection behavior, the reflected light passing through the beamsplitter to the eyepiece will always focus on the same place laterally in the eyepiece object plane, which is exactly conjugate to the pinhole light source. If the objective is not in good focus on the surface, the reflected spot will be out of focus but always centered in the same location independent of the tilt of the surface. At best focus, the image in the eyepiece object plane will be the same size as the pinhole in the source. Notice that this is the same type of behavior as putting a cube corner reflector in front of an autocollimator; the reflected light spot is stationary even when the cube corner is no longer square with the axis of the autocollimator.

The other location where reflected light returns to the ASM is if the focus of the objective is at the center of curvature of a spherical surface, as in Fig. 3a, where the objective is focused on the center of the ball, here used as a convex mirror. Light rays exiting the objective follow normals to the surface of the spherical ball, and light is reflected back along the normals into the objective. If, however, the focus of the objective is slightly to the side of the center of curvature, as in Fig. 3b, the return light will focus on the opposite side of the center of curvature. This makes the ASM very sensitive to alignment with the center of curvature of a spherical surface. Just as in the case of the Cat's eye reflection, if the objective focus is not coincident with the center of curvature along the line of sight to the surface, the return spot of light will be out of focus.

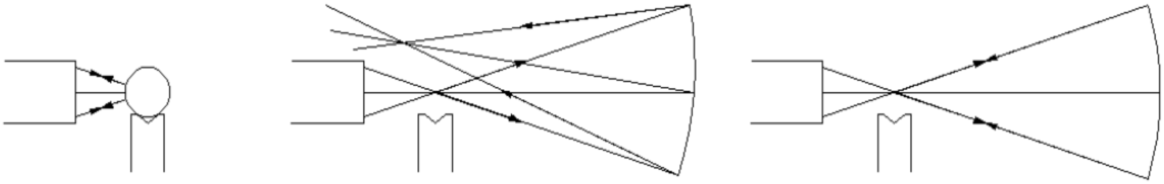

Fig. 3 Objective focused at the center (of curvature) of a ball, or convex mirror (a), focused near the center of curvature of a concave sphere (b) and focused precisely at the center of curvature (c)

With this background, it is easy to see how an ASM can be used to measure the radius of curvature of a lens or mirror surface. First, focus the ASM on the surface near its center, and the Cat's eye reflection will appear in good focus when the ASM is precisely focused on the surface. Adjust the crosshairs or other reference in the eyepiece on the return spot, as this reflected image is conjugate to the light source and on the optical axis of the ASM.

Then move the ASM to focus at the center of curvature of the surface by aiming the ASM roughly at the center of the surface and moving in 3 degrees of translation until the return reflected spot lies centered on the eyepiece crosshairs or reference. The ASM is now precisely located at the center of curvature in 3 degrees of freedom. Note the position of the ASM mount on a rule or straightedge lying between the ASM and the surface. Move the ASM along the straightedge until the Cat's eye reflection is again in focus and note the scale reading. The difference in the 2 readings, as shown in Fig. 4, is the radius of curvature of the surface. Note that moving along a straightedge from a position where the ASM was centered at the center of curvature means that the ASM is moving along a normal to the sphere, and a true reading of the radius of curvature will be achieved.

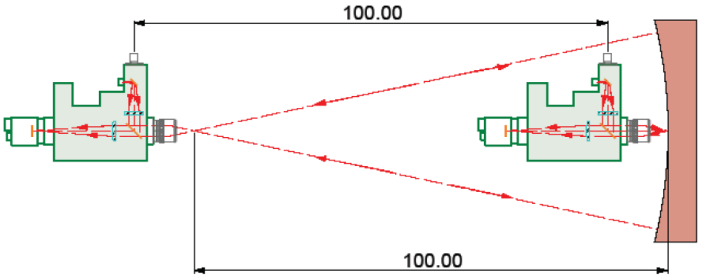

Fig. 4 Use of an ASM to measure the radius of curvature of a concave mirror

Notice also that this method works equally well for convex surfaces as long as the objective has a long enough working distance to accommodate the radius of the surface. Another issue to remember is that the laws of physics still apply to radius measurement. If the surface being measured has a small diameter relative to its radius of curvature, there will be difficulty finding the best focus due to the slow f/# of the light cone. On the Cat's eye side, a higher magnification objective permits greater sensitivity to focus, but at the center of curvature, it may throw away too much light beyond the edge of the surface. Generally, use a low magnification objective like 5x for slow surfaces and a 10 or 20x objective for fast surfaces.

My introduction to autostigmatic microscopes

My first job after graduating from college with an MA in Physics and no formal optics education was at Eastman Kodak Company. Virtually the first thing they had me do was measuring the radius of curvature of test plates, the master surfaces against which lens surfaces would be checked using Newton ring interference. The measurement was done with an ASM whose make I forget, but it could have been one from Gaertner Scientific[5], a company that still sells all the parts needed to make an ASM. Another project at Kodak got me into the job of aligning one optic to another, but the idea of using an ASM as an alignment device did not occur to me.

From Kodak, I went to Itek Corporation (now a part of Goodrich) in Lexington, MA. One of my jobs there was to adjust the 6 cameras in the S-190 survey instrument, flown on Skylab in the summer of 1973, for matched distortion and magnification. Each camera operated in a different spectral band, and the idea was to overlay the 70 mm format negatives from the different cameras and have details in the film match up to +/- 1 µm. This meant each nominally 150 mm focal length camera had to be adjusted to have nearly identical field heights at the edges of the field even though some of the spectral bands were outside the visible spectrum into the NIR.

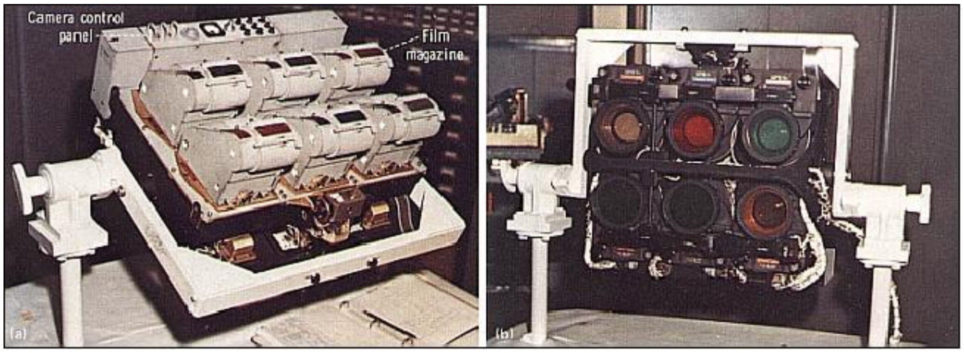

Fig. 5 S-190A Multispectral Photographic Camera System found at https://directory.eoportal.org/web/eoportal/satellite-missions/s/skylab

We used a nodal slide lens bench to do the measurement and projected a collimated beam of white light from a pinhole source into each camera. The point images in the camera focal planes were detected with a microscope with a quad-cell photodetector in the eyepiece object plane. There was a beamsplitter so that the images could be viewed either visually or electronically. The visual image allowed us to get things aligned initially, but the data were taken for all 6 cameras using the electronic quad cell, so all the distortion and magnification data were treated the same. Using a microscope with an electronic detector put another piece of the ultimate ASM design in the back of my mind.

From Itek, I went on to work at Frank Cooke, Inc. in central Massachusetts and learn how optics were made instead of just testing them. One of the optics made there were hyper-hemispherical glass domes about 180 mm in diameter and 6 mm thick. There was a reasonably tight spec on the concentricity of the inner and outer surfaces of the dome, that is, the centers of curvature of the 2 concentric surfaces were supposed to be within 50 µm of each other in all 3 degrees of freedom.

Raymond Boyd was Cooke's metrologist and had formerly worked for American Optical in Southbridge, MA. To test for concentricity, Ray made a pseudo-ASM by inserting a piece of optical fiber into a filar eyepiece, much as in Fig. 6.

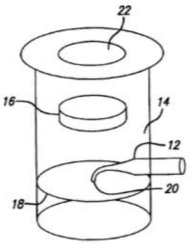

Fig. 6 Illustration from US Patent 6,924,897 showing an eyepiece with a fiber point light source. 12 is the fiber preform, 20 is the drawn-out tip, 18 is the eyepiece focal plane and 16 is the eyepiece lens

Ray had worked with Elias Snitzer, one of the early inventors of fiber optics at American Optical, and had access to fiber optic pre-forms that were about 3 mm in diameter. Ray would use an alcohol flame to draw the preform out into a small diameter fiber and bend the tip 90 degrees to make a rudimentary point source. He used a microscope illuminator focused on the large end of the preform as the light source. When the fiber tip was at the centers of curvature of the dome, point images were returned from both surfaces and the distance separating them could easily be measured with the filar scale in the eyepiece focal plane.

This simple optical device could do in minutes what would otherwise be a complex mechanical metrology problem requiring a good rotary bearing and several contact measurements along with some math to determine the same knowledge of the concentricity of the surfaces. We used similar fibers to test such things as fast elliptical reflectors, as described in a brief paper[6] I wrote after moving on to run the Optics Shop at the Optical Sciences Center at the University of Arizona.

While at Optical Sciences, I found that EG&G was making a professional eyepiece for a radiometric instrument they sold that was almost identical in function and design to the one Ray Boyd had used at Cooke's. EG&G used the eyepiece backward to how we intended to use it; the fiber tip picked up the light coming toward the eyepiece from the sample being viewed, and a fiber bundle took that light to a sensitive photometer to record its value.

We illuminated the end of the fiber bundle with a bright source and let the light exit the fiber tip in the eyepiece headed out of the microscope through the objective. When the objective was focused on a specular surface the light from the fiber came back in retroreflection directly on the fiber tip in the eyepiece. This was a great, commercially available solution to making a point source eyepiece for an ASM. Unfortunately, not many years later, EG&G stopped making these eyepieces.

About this time, I left the University to start a consulting company called Optical Perspectives Group, LLC, along with a colleague, William P. (Bill) Kuhn. One day, we got a call from a local company that had designed a complex lens for a laser writer system they were making. The system had 6 lenses, some of which were rectangularly edged toroids and a spherical mirror, all of whose centers of curvature were supposed to lie on a straight line. Our job was to develop a method of aligning the lenses and mirror to do so.

We immediately recognized this was a perfect job for an ASM that we put together with Thorlabs parts and an analog CCD camera. The ASM was mounted in the chuck of a milling machine, and the optical bench holding the lens elements was set on the mill table that we used for a large x-y-z stage. With this setup, we could get to the centers of curvature of all the elements by cranking the mill table over the length of its travel. In the case of the toroidal lenses, we would get back a line image instead of a circular spot, but the line was just as easy to align as the spot.

Using this crude ASM and the mill, we were able to align the lens system in about 4 hours and get better performance from it than they had previously achieved by another method that took about 2 weeks. The company was delighted, but the system needed to be assembled in a clean room environment, and they could not put the mill in the clean room.

This was the beginning of the original Point Source Microscope (PSM), an ASM small and light enough to be held on the ram of a coordinate measuring machine (CMM) instead of the usual mechanical touch probe. Many technological advances have been made over the years since the ASM was put together at Cooke's. There were affordable CCD cameras and single-mode fiber light sources in the visible. Also, the design of microscopes changed from finite conjugate to infinite conjugate versions, where the light between the objective and the "tube lens" was collimated. This change made customizing microscopes much easier since the distance between the eyepiece and the objective was not fixed. It also meant that in reflecting microscopes, the beamsplitter that was necessary to introduce the light from the source no longer introduced aberrations into the converging beam of light as was the case in finite conjugate microscopes.

An initial problem with the new PSM was there was no way to mark where the Cat's eye reflection returned on the detector. Our initial solution was to place a Magic Marker dot on the analog monitor faceplate. This worked but was neither elegant nor precise. We then realized that a Shack cube, such as used in a Shack cube interferometer[7], would be just what was needed to produce a reference spot of light to be the indication of where to bring the light to focus from the center of curvature of the surface we were trying to align. Fig. 7, taken from US Patent 6,924,897, shows the original PSM layout and the Shack cube (#30a and b).

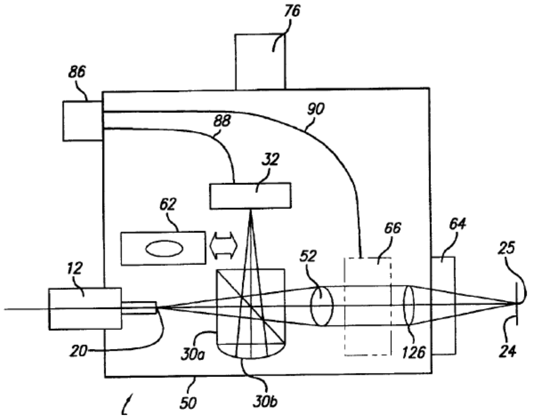

Fig. 7 Layout of the original Point Source Microscope

The Shack cube is a cube beamsplitter with a plano-convex lens cemented to one side so that its center of curvature is conjugate to the tip of a single-mode optical fiber (20) and the analog CCD camera. The objective is #126, and the tube lens is #52, with collimated space in between. While this design worked very well for our customer, we realized almost immediately that this was not a very smart design; once the return spot was centered behind the reference spot, there was no way to center any better. This limited our centering ability to about 5 µm. At the same time, useful camera and software technology was changing rapidly.

Bill looked at a combination of the shortcomings of this original design and at the advances in technology to come up with what is now sold as the Point Source Microscope (PSM), and is shown schematically in Fig. 8. There are many improvements on the original, but the one to address the major flaw of the first was to use a digital CCD camera coupled with National Instruments LabView software that could centroid on the return spot of light. This meant that when the Cat's eye spot was first obtained in good focus, the software could place an electronic crosshair on the video display to define the lateral zero position on the display to a fraction of a µm. Other return spots could then be located relative to the crosshair to the same precision.

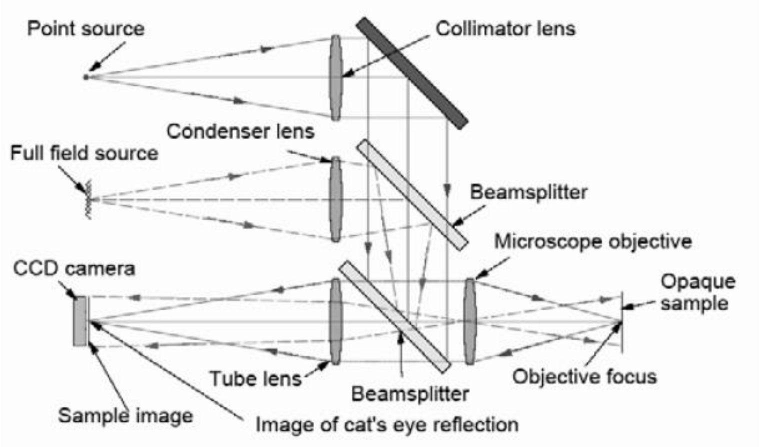

Fig. 8 A schematic diagram of the optical paths within the PSM

Returning to Fig. 8, other new features included an internal LED light source and diffuser to provide Kohler illumination for full-field imaging. Then, the PSM could be used both as an ordinary video microscope and an autostigmatic one for alignment purposes. Where the original PSM had an external fiber source, the new one had an internal single-mode fiber pigtailed to a red laser diode. The two light sources are adjusted so the autostigmatic focus is parfocal with the full field image plane. Another feature of the laser diode light source is its bright and dim mode. In the bright mode, the light is bright enough to be seen under ambient lighting so that it is easy to find the return reflected light spots. However, this intensity is sufficient to saturate the camera in most cases, so the dim mode is used for the electronic centroiding.

A further feature is the use of infinite conjugate optics, so when the objective is removed from the PSM, it becomes an autocollimator. Thus, the PSM is three distinct instruments in one: a video imaging reflecting microscope, an autostigmatic microscope, and an autocollimator with a large angular capture range.

Using the PS for alignment

Now that the development of the PSM and the use of it to measure radii of curvature have been described, we will describe a simple but non-trivial alignment situation. Assume we want to align the optics in a 2-mirror grating spectrometer that, when aligned, looks like Fig. 9. We will assume that the 2 slits and the axis of the grating are fixed by the mechanics of the lens bench on which the optics are mounted. From a combination of the mechanical and optical drawings of the instrument, we know where the centers of curvatures of the collimating mirrors should be relative to the slits and grating axis before the optical path is folded to the slits. Further, the 2 fold mirrors should be set so that light focused at the entrance slit exits, in focus, at the exit slit. Also, assume that all 4 mirrors that will be aligned are held in mounts with 3 adjustment screws so they may be tilted in 2 directions and displaced axially in the direction of the screws by turning all 3 simultaneously.

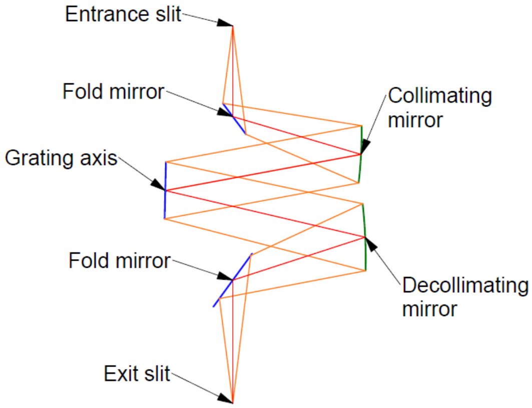

Fig. 9 A two mirror grating spectrometer in its final configuration

Fig. 10 shows where the centers of curvature of the collimating mirrors are (violet) and where they are reflected in the fold mirrors (blue) when the fold mirrors are properly aligned.

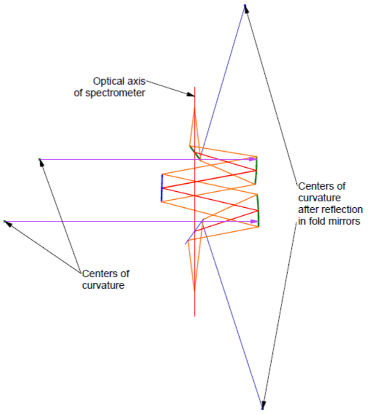

Fig. 10 The center of curvature locations of the collimating mirrors directly and as folded

To perform the alignment, the optical bench on which the mirrors are mounted, along with the grating, are temporarily pinned to an alignment fixture plate into which holes have been bored at the center of curvature and slit locations. Into these holes, a post is placed on the top of which is a spherical steel ball. An example of this type of fixture is shown in Fig. 11, where the posts are lens mount posts, and the balls sit kinematically located in the conical chamfer in the posts. A collar on the post keeps the distance above the fixture constant.

In Fig. 9, the PSM is focused on the center of a steel ball located where the center of curvature of the relay mirror in the black optical bench should be located relative to the bench as defined by the aluminum plate fixture and the pinning of the bench to the alignment plate. This approach permits the alignment to tolerances that are as good as the balls can be located mechanically.

Fig. 11 The PSM focused on the center of a steel ball sitting on the post located in the bored hole in the aluminum alignment plate.

In the case of the spectrometer, the same approach is used. First, a post and ball are placed at the center of curvature of the collimating mirror. The PSM on a 3-axis stage is placed facing the mirror and adjusted until the objective focus is at the center of the ball in all 3 degrees of translational freedom. Half-inch diameter balls (Grade 5) are excellent convex mirrors. The ball is removed from the post so the light from the objective illuminates the mirror and is refocused near the objective focus. The 3 screws on the mirror are used to bring the center of curvature of the mirror to the precise focus of the objective in all 3 degrees of freedom. This is why 3 adjustment screws are needed on the mirror so that the mirror can be adjusted not only in 2 angles but in axial translation to get the best focus as well.

This step is repeated for the decollimating mirror. The post is moved to that hole in the plate, the PSM is moved over and focused on the center of the ball, the ball is removed, and the mirror is adjusted with the 3 screws. Note how the PSM is used to place an optical conjugate that cannot be touched physically in proper relationship to a feature that is mechanical and can be touched probed mechanically. The PSM is a transfer device from an ethereal optical conjugate to a rigid mechanical datum or vice versa.

Now, the fold mirrors can be adjusted by using holes located where the centers of curvature should appear as reflected in the correctly adjusted fold mirrors. In Fig. 11 there are a set of 4 holes toward the front edge of the alignment plate. The hole nearest the edge of the plate is where the center of curvature of the relay mirror is after the fold mirror is installed in the black optical bench. The idea is the same for the spectrometer. The PSM is set up facing the fold mirror and centered on the ball. The fold mirror is then adjusted in 3 degrees of freedom until the center of curvature is centered on the PSM focus. Notice that it takes 3 adjustments on the plane fold mirror to accomplish this alignment.

Once both fold mirrors are adjusted, a post and ball can be placed where the exit slit is to go. The PSM is aligned to a ball at the entrance slit as in Fig. 12. Only if the grating is adjusted so the double pass reflection of the entrance slit lies on the exit slit will light return to the PSM focus. This establishes the zero setting of the angle on the grating rotation axis and allows a correction for any tilt in the orthogonal direction.

Another aspect of this final alignment is that the return spot to the PSM will not be a perfect spot but will be aberrated due to the optical design of the spectrometer. However, the aberrated spot should be of a size and shape consistent with the design of the spectrometer. If it is not the expected spot, it is clear something is wrong with one or more of the optics. A serious figure error in any of the optics will be noticed at each previous step in the alignment. The PSM can sense asymmetry in the image down to a level of 1/8th to 1/10th wave. If there are figure errors of these magnitudes, they will be apparent in the "Star test[8] image" as each optic is aligned. This means that errors in assembly can be caught before the entire system is put together and before figuring out which element is to blame for the system's lack of design performance.

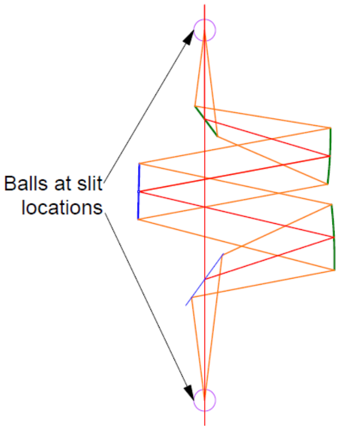

Fig. 12 Check of the grating zero angle by double passing the spectrometer off a ball at the exit slit

Conclusion

We have explained what an autostigmatic microscope is and how it can be used to measure optical surface radii. I have also described how a modern version of an ASM was developed over several years as my familiarity with its use expanded and as technological advances were made in many useful components that became part of the final Point Source Microscope. Finally we showed an application of using the PSM for alignment of optical components and showed how an ASM acts as a transfer device from ethereal optical conjugates to fixed mechanical references.

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