Autocollimator and Point Source Microscope

Introduction: The first portion of this lab uses an autocollimator to aid in aligning optics. Light from the autocollimator is projected out into space. Light reflected from surfaces in space return autocollimator and are focused onto a microscope reticle. Tipping and tilting the optics moves the focused spot relative to the reticle. When the focused spot and the reticle are aligned, the autocollimator axis of the optic are coaxial. This process is repeated for additional optics. Sometimes lenses in the lab are mislabeled and it becomes necessary to determine its paraxial parameters. The second portion of the lab, uses a Point Source Microscope (PSM) to find the four paraxial parameters found in the lens maker’s equation. By measuring six adequate distances, and using a spreadsheet program you will find the unknown parameters.

12.1.3 Techniques using a "Point Source Microscope" Parks and Kuhn3 and Parks46 have described several techniques for using a "point-source microscope" (PSM) as an alignment device for optics. Figure 12.10 is an exterior view of the instrument. Its optical schematic is shown in Fig. 12.11. There are two light sources. The one in the top portion of the instrument is a -- 4.5-µm diameter, f/5 divergence point source created by a single-mode optical fiber pigtailed to a laser diode (not shown) operating at 635-nm wavelength. The collimating lens following the point source creates a diffraction limited "artificial star" at infinity for the microscope objective. A point image of the source is then produced at the focus of that objective. The source in the center portion of the PSM is a diffuse extended source (ground glass disc) back-illuminated by a red light emitting diode. A condenser lens provides Kohler illumination by reimaging the extended source to fill the pupil of the microscope objective. A beamsplitter combines these two beams and a second beamsplitter folds both beams into the objective.

ALIGNING REFRACTING, REFLECTING, AND CATADIOPTRIC OPTICS 521

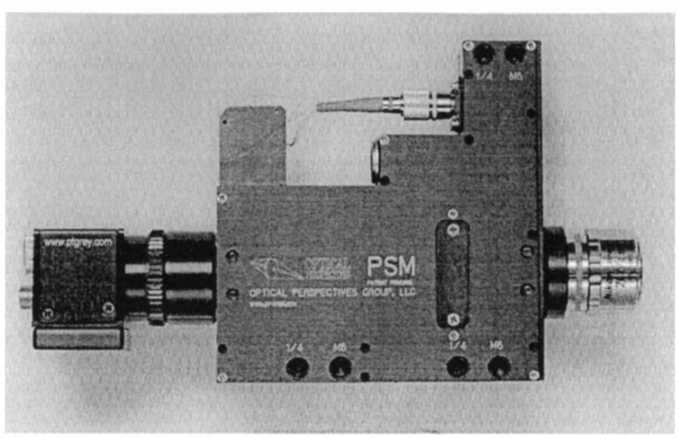


Figure 12.10 Photograph of the point-source microscope. (Courtesy of Optical Perspectives Group, LLC, Tucson, AZ.)

Figure 12.10 Photograph of the point-source microscope. (Courtesy of Optical Perspectives Group, LLC, Tucson, AZ.) The lowest sketch in Fig. 12.11 shows the beam reflecting from a test surface located at the focus of the microscope objective to a CCD video camera. This is often called a "cats eye" reflection. If the surface of the test object is flat, specular, and approximately normal to the axis, the beam from the point source is returned as a "point" image at the CCD camera. If the test object surface is a convex sphere (or a paraxial region of an aspheric), specular, and located with its center of curvature at the objective focus, the beam from the point source is returned as a "point" image at the CCD camera by retroreflection. If the test object surface is flat and nonspecular, the beam from the extended source is returned to form an image of that surface at the camera. The camera can be adjusted to center any of these images to an electronically generated crosshair on a video monitor. Usually, the PSM is mounted on a three-axis linear stage so it can be aligned to the test object and moved axially to access various images. The axial stage is provided with means to measure distances moved so the PSM can be used to measure surface radii. For example, view (a) of Fig. 12.12 shows a convex spherical surface positioned at the objective focus to produce a "cats eye" reflection. View (b) shows the PSM moved closer to the surface so the retroreflection from the center of curvature is in focus at the camera. The distance moved is the radius of the surface. The radius of a concave surface can be measured by a simple adaptation of this procedure. This function of the apparatus is especially useful as a means for non-contacting inspection of optics and for calibrating optical test plates. The PSM can be used to monitor alignment errors during assembly of lenses by focusing it on each center of curvature in sequence. If the lens is on a precision spindle, a misaligned surface will return an image that nutates as the spindle rotates. It is necessary for either the PSM or the lens to move axially to access the two returned images.

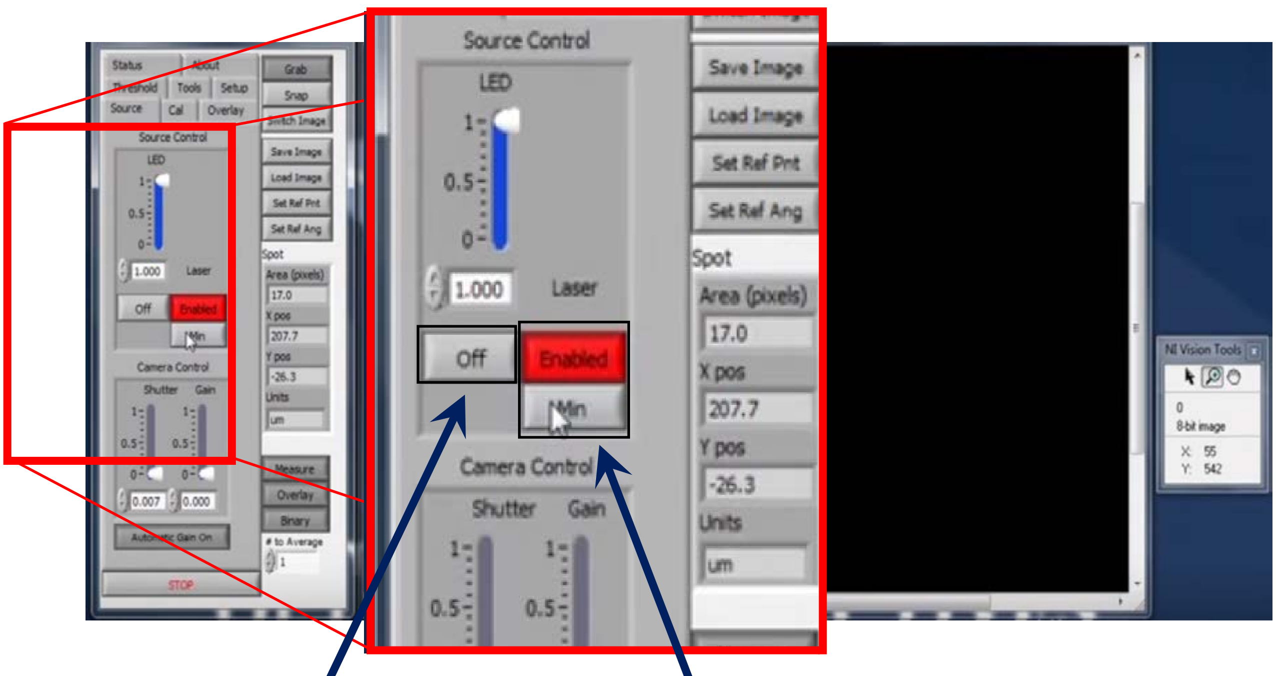
The excel spreadsheet can be download at
http://www.optiper.com/downloads/item/measuring-the-four-paraxial-lens-parameters-using-an-autostigmatic-microscope

Where is “Solver” in Excel?
https://www.youtube.com/watch?v=Q3ciB1ED4_A

The computer in lab (Rm 436) does not have Excel. Please Add-in Solver to your computer. The computer has the PSM software. Solver is also installed on the computer. Please save your screen shots to a word document and save that in the 515L “star” folder on the desktop under Lab 4 and your lab day.

To complete this lab you will need to familiarize yourself with a Point Source Microscope (PSM). An excel file is provided to determine paraxial parameters of a provided lens. There are six unknowns that need to be measured. These unknowns are yellow cells in the Excel file. You will need to input estimations (green cells) to use solver (part I).

Autocollimator Alignment – Set up the autocollimator and familiarize yourself with its operation. We will create a mock system with a prism it in to fold the optical path. Place a prism in front of the autocollimator. View the retro-reflected points and adjust prism so the reflection from the incident and emerging faces are aligned as best as possible. Next, place a plane mirror in the space following the beam emerging from the prism. Tip and tilt the mirror to make it normal to the optical axis. Add a lens between the prism and the plane mirror and align it to the optical axis. Finally, add another optical element between the prism and autocollimator and align it.



LED control

Use to image lens surface

Red box -> LED ON

Laser controls

Min/Max setting

Red box -> LED ON

I. Determining Estimations (green cells)

1) Look up the index value for BK7 **(n)**
2) Use sphereometer to measure sag and calculate radius of curvature for both surfaces of the lens **(R1 and R2).** Note which side is which.
3) Use calipers to measure the center thickness of the lens (do not scratch lens with calipers) **(t)**

II. Finding Thicknesses t1 and t2

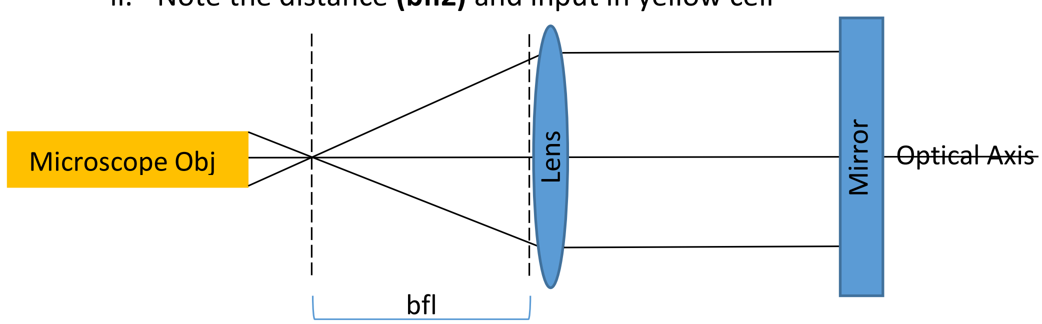
1) Enable Laser and Max setting (both Laser controls should be RED)
2) Locate the focal point of the Microscope Objective.
3) Place a bi-convex lens in the path of the laser light. Make sure the lens is on the same optical axis as the laser light.
4) Translate the lens so that a spot on the computer screen is at its smallest

    i. Take a screen shot of what you see and note location on rail

5) Turn off the laser and enable the LED (turn RED) and image the surface of the lens
    i. Take a screen shot of what you see
6) Turn off LED and enable laser (max not needed). Translate the lens until you see another spot come into view and minimize.
    i. Take a screen shot of what you see and note the distance you traveled from the first spot position. This is your thickness **(t1)** (input as negative). Write this value in the yellow excel cell.
7) Turn off the laser and enable the LED (turn RED) and image the surface of the lens
    i. Take a screen shot of what you see
8) Turn lens around and redo steps 1-7 to find **(t2)** (input as negative).

III. Finding BFLs

1) Turn off LED and enable laser (turn RED).
2) Do not remove the bi-convex lens
3) Use a flat mirror on a tip/tilt mount and place it to the right of the lens.
4) Tip/tilt the flat mirror so the reflected light focuses on the left side of the lens in the same position as the focal point of the microscope objective, use auto collimation technique to check this
5) To achieve this you will need to translate the lens to the right (away from microscope objective) to a point where the spot is smallest on the CCD/computer screen. The distance from the microscope objective point to the front surface of the lens is the first **(bfl1)**.
    i. Take a screen shot of what you see
    ii. Note the distance **(bfl1)** and input in yellow cell
6) Turn the lens around and redo steps 4 and 5. Find **(bfl2)**.
    i. Take a screen shot of what you see
    ii. Note the distance **(bfl2)** and input in yellow cell



IV. Finding d1 and d2

1) Remove flat mirror
2) The second surface of the lens acts as a concave mirror and will reflect the light.
3) Move the lens to the point where the light reflecting off the second surface focuses back onto the same position as the focal point of the microscope objective
    i. Record position of lens on rail
4) Move the lens to the point on the rail when the rear surface of the lens is imaged, same techniques used as in part I when finding the thickness, use LED and Laser light. Screen

shot what you see (both LED (surface shot) and Laser spot). Record that position on the rail

5) Subtract the two recorded points = **(d1)**
6) Turn around the lens and complete steps 3-5 to find **(d2)**.
7) Input these values into the designated yellow cells in excel.

V. Using solver

1) Once all green and yellow cells are filled, use the Solver Add-in at the top right under the “DATA” tab. The purpose of using Solver is to minimize the “sum of squared differences” (orange cell).
2) With Solver screen open, make sure the “Value of:” is selected and has an input of 0. Do not change the constraints.
3) Press “Solve”
4) Keep Solver solution
5) If the value in the orange cell is not close to 1, perform step 3 again, or until it is close to 0.

applied optics

Measuring the four paraxial lens parameters using an autostigmatic microscope

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We describe a method of measuring the four paraxial lens parameters—the two radii, the center thickness, and the index—of a realistic-size positive lens using an autostigmatic microscope (ASM). The method is similar to measuring the radius of curvature of a concave mirror with an ASM but slightly more complex in that four characteristic distances must be measured to solve for the four unknown parameters. Once the four distances are measured, it is shown how to use an Excel spreadsheet and the add-in iterative "Solver" to find the four unknown parameters. Finding the paraxial lens parameters is useful for troubleshooting a lens assembly that does not perform as expected due to mislabeling, the incorrect glass type used, insertion into the assembly backward, or for finding a replacement glass type.

OCIS codes: (080.0080) Geometric optics; (080.2468) First-order optics; (080.1753) Computation methods; (080.3630) Lenses.

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1. INTRODUCTION

Occasionally, it becomes necessary to determine the paraxial lens parameters [1] of a singlet lens because the lens was mislabeled, perhaps inserted in an assembly backward because the two radii were close, the wrong glass was mistakenly used in manufacture, or the lens must be reengineered because the glass type is no longer available. For whatever reason, these four paraxial parameters found in the lens maker's equation must be determined, that is, the two radii, the center thickness, and the index.

This is quite easy to do using an autostigmatic microscope (ASM) [2], which is an optical instrument similar to an autocollimator but with a finite focus. The four paraxial parameters are found in much the same way as when an ASM is used to measure the radius of curvature of a concave mirror [3]. Because most lens elements are positive, we will use this case as an example but also indicate that much the same method works equally well for negative elements with the addition of a concave mirror.

First, we describe an example positive lens and explain why it is a typical example. Then, we indicate the distances, or thicknesses, which have to be measured and give paraxial equations for these derived from the lens maker's equation. We discuss which of the possible measurements are most sensitive and select those as the measurements to perform. Finally, we show how to solve for the unknown parameters. There may be a closed-form solution, but it is straightforward to use a spreadsheet program along with a built-in iterative equation solver to find the desired results.

2. EXAMPLE LENS

The positive singlet used to illustrate the procedure has a back focal length (BFL) of 100 mm and a clear aperture of 24 mm and is designed for use at infinite conjugates (see Fig. 1). As such, it is typical of many lenses that might require paraxial parameter determination in that the radii are too long to be within the typical working distance (10–20 mm) of a microscope objective that might be used on an ASM. This means that neither of the lens radii can be measured directly at their centers of curvature as described in [3].

On the other hand, when looking into the lens from either side, the far radius of curvature will appear concave and will be easily accessible by the ASM. Also the BFL is easily measured against a plane mirror because this is a positive lens. Using a Cat's eye reflection off either of the rear surfaces looking in from either side, the apparent center thickness also can be measured, but it is the least-sensitive thickness to use in solving for the required parameters because it is small compared with the other distances.

3. PARAXIAL EQUATIONS

The lens, as it would normally be used to focus light from infinity, is shown in Fig. 1 with R_1 as the first surface. In making the distance measurements, the ASM is looking at the lens from the right, and, if we were measuring the BFL, the ASM focus would be at the place where the rays focus in Fig. 1. For this discussion, we note that R_1 stays with the lens when it is reversed and will always be 65.730 mm, but the sign will change. Also, the

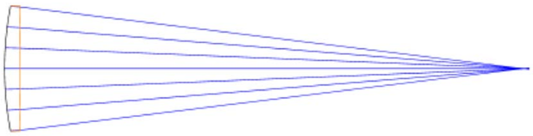

Fig. 1. Example lens with a back focal length (BFL) of 100 mm designed for use at infinite conjugates. $R_1 = 65.73$, $R_2 = -841.804$, $t = 3.0$, $n = 1.60$.

zero distance for all measurements will be the surface facing the ASM, R_2 in the case of Fig. 1. Distances to the right of R_2 are positive.

By paraxial ray tracing, the optical center thickness of the lens is found to be

$$t_o = \frac{-R * t}{[t * (n - 1 + n * R)]}, \tag{1}$$

where t is the physical thickness, n the index, and R the radius of the surface facing the ASM, R_2 in Fig. 1 with the sign changed. This gives

$$t_0 = \frac{841.804 * 3}{3 * (1.6 - 1) + 1.6 * -841.804} = -1.878, \tag{2}$$

which is a small number relative to the radii we are trying to determine. This is not much help in solving for the radii but useful as a quick check of center thickness without having to physically touch the lens surface. If the lens were reversed, we would find $t_0 = -1.843$ mm.

Again by paraxial ray tracing the center of curvature of R_1 looking into the lens from the right is given as

$$R_{o1} = \frac{-R_2(R_1 - t)}{(R_1 - t)(n - 1) - nR_2} = 38.140 \text{ mm}. \tag{3}$$

If the lens is reversed, we simply exchange R_1 and R_2 in the formula and change the signs of each as well to find $R_{o2} = 90.6148$ mm. In both cases, these are measured with respect to the surface closest to the ASM.

In a similar manner, it can be shown that the BFL of the lens is given by

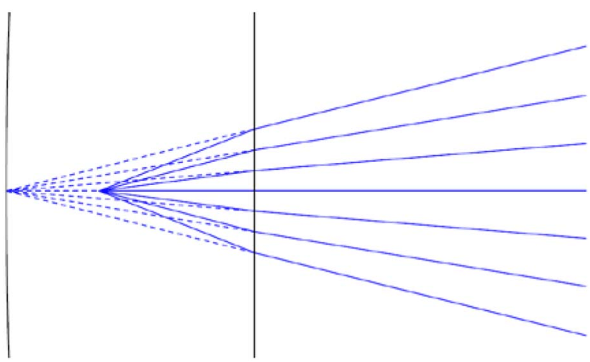

Fig. 2. Central part of the lens showing rays coming from the right from the ASM objective focused 1.878 mm into the lens but appearing to come (dashed lines) from the far vertex Cat's eye reflection due to refraction at the surface nearest the objective.

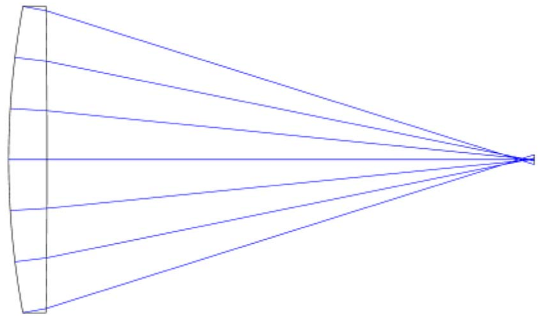

Fig. 3. Rays coming from the center of curvature of R_1 after refraction in R_2 and focusing at $R_{o1} = 38.140$ mm from R_2.

$$bfl_{o1} = \frac{R_1[t - n(R_2 + t)]}{(n - 1)[t + nR_1 - n(R_2 + t)]} = 101.606 \text{ mm}. \tag{4}$$

To find bfl_{o2}, we do the same thing: substitute R_1 for R_2 and change signs of both to get $\text{bfl}_{o2} = 100.000$ mm.

Figures 2 and 3 show the rays for the center thickness and radius of curvature, while Fig. 1 shows the case for bfl_{o2}. In Fig. 2, the ASM is focused at 1.878 mm into the 3 mm thick lens, but the Cat's eye reflection appears to be coming from the vertex of the far surface.

In Fig. 3, the rays are refracted at the surface closest to the ASM, so they reflect from the far surface at normal incidence.

4. CALCULATION OF THE LENS PARAMETERS

We now have a total of six thickness measurements, three from each side of the lens. We put these values, the highlighted numbers in yellow, into the Excel spreadsheet, as shown in Fig. 4.

To use the spreadsheet, estimates for the four paraxial lens parameters are entered in the boxes highlighted in green. Immediately below these boxes are calculations of what the six measured thicknesses should be based on the initial

Lens parameters/calculated or measured values	Initial estimates of lens parameters		
Estimated value for index, **n**	1.600		
Estimated value for physical thickness, **t**	3.000		
Estimated value for first surface radius, **R1**	841.804		
Estimated value for second surface radius, **R2**	-65.730		
	Calculated thickness based on lens parameters above	Measured thickness from surface nearest ASM	Squared difference between measured and calculated
Thickness from R2 surface to focus, **d1**	90.615	90.615	6.65345E-08
Thickness to R1 vertex from R2 surface, **t1**	-1.908	-1.908	1.22885E-12
Reverse, thickness from R1 surface to focus, **d2**	38.140	38.140	5.18067E-09
Reverse, thickness to R2 vertex from R1, **t2**	-1.878	-1.878	1.15354E-12
Distance from R2 surface to focus, **bfl1**	100.000	100.000	1.32115E-08
Reverse, distance from R1 surface to focus, **bfl2**	101.606	101.606	2.49799E-08
Sum of squared differences			1.09909E-07

Fig. 4. Spreadsheet used to calculate lens parameters from six thickness measurements. Values highlighted in yellow are those obtained by measurement while those to the left are based on first-order calculations. This example shows the results (in green) based on "perfect" measurements.

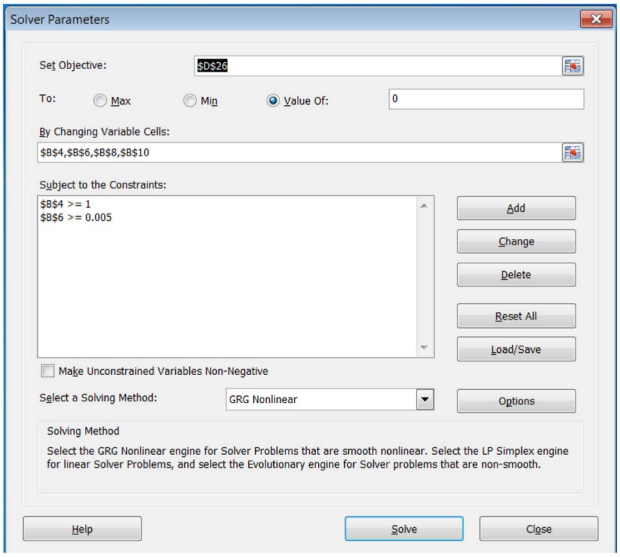

Fig. 5. "Solver Parameters" window filled in for the example data shown in Fig. 4.

estimates. The yellow highlighted numbers are filled in based on the measured thicknesses, and there will always be small differences between the calculated and measured values. The square of these differences, to keep the differences positive, are shown in the last column and the sum of the squared differences in the last box (highlighted in orange). Note that the third, fourth, and sixth distances all assume the lens is reversed and that the R_1 side is now toward the ASM, which is pointed toward the lens from the right.

To find the four unknown lens parameters (highlighted in green), it is necessary to make the square of the sum of the differences (in orange) as small as possible. To do this, the "Solver" add-on in Excel is used [4]. First, the Solver must be installed in Excel and then the "Solver Parameters" menu set up. To get here, once the Solver is installed, click on the Excel "Data" tab and then "Solver" at the far right.

In the Solver parameter box (see Fig. 5), put the value that is the sum of the squared differences in the "Set Objective" box because this is what we want "To" have a "Value of" 0. We get this "By Changing Variable Cells" with the estimates of the four lens parameters. The "Constraints" are added using the "Add" tab and keep the index >1 and the thickness $>$ than some small number. Be sure the "Make Unconstrained Variables Non-Negative" is unchecked because at least one radius will be negative.

In general, a solution will be found using the setup as shown, but a better solution, one with higher precision, can be found by clicking the "Options" box and adding some zeros to the "Constraint Precision" box and under "GRG Nonlinear" adding some zeros to the "Convergence" and checking the "Central" derivatives box. Then hit the "Solve" button, and an answer should appear for the four lens parameters. If the results of the measurements were not too precise, the Solver may come back and say "No Solution Found" because it cannot make the sum of the squares as small as the number of zeros in the "Convergence" box. You can either accept the solution as good enough as it is or loosen the convergence until the Solver finds a solution.

5. DISCUSSION

Although the example is for a bi-convex singlet lens, it should be clear that the same basic method applies for any form of positive lens. If the lens is plano–convex, simply use a large number like 1e10 for the plano side in the spreadsheet [5]. It is easy to make an error in sign or get the surfaces reversed in the calculation; thus, common sense must be used if the answers do not seem to match the experimental situation.

For negative lenses, the same approach can be used, but a concave mirror must be used to create a real focus that the ASM can access. The concave sphere must have enough power so the combination of sphere and lens form a positive optical pair. Obviously, the spreadsheet and formulas must be adjusted to take the sphere into account, but the methodology of the process is exactly the same.

6. CONCLUSION

It has been shown how to solve for the four paraxial lens parameters of any positive lens by measuring a set of at least four distances so there is sufficient data to solve the set of equations. The distance measurements are similar to those made when measuring the radius of curvature of a concave sphere with an autostigmatic microscope. There does not appear to be a closed-form solution to finding the lens parameters, so a spreadsheet is used along with an iterative equation solver to find the four lens parameters simultaneously.

For those more versed in lens design, the paraxial parameters also can be found using a four (or more to match the situation) configuration design for the measured distances. Here, the lens design optimizer is generally constrained enough that estimates for radii can be plano surfaces and the index and thickness almost any positive values. Again, it is possible to find the paraxial parameters for a negative lens by adding a concave sphere to the test setup to force the pair of optics to produce a real image between the lens and the ASM.

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