The Autostigmatic Microscope and Its Uses

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- Examples include telescope systems, spectroscopic instruments, commercial optics, and many others

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- Build community
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    - Over 70 members so far, please join!

- Resource for members
    - Topically relevant webinars, like this one!

Our Speaker – Robert Parks

- BA and MA in Physics from Ohio Wesleyan University and Williams College (respectively)
- Has worked at Eastman Kodak Company, Itek Corporation, and Frank Cooke, Inc.
- In 1976 he went to the Optical Sciences Center, University of Arizona, to manage the optics shop and was promoted to Assistant Research Professor
- He started Optical Perspectives Group in 1992 and is still active there

The Autostigmatic Microscope and its Uses

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and Davidson Optronics/TriOptics-USA
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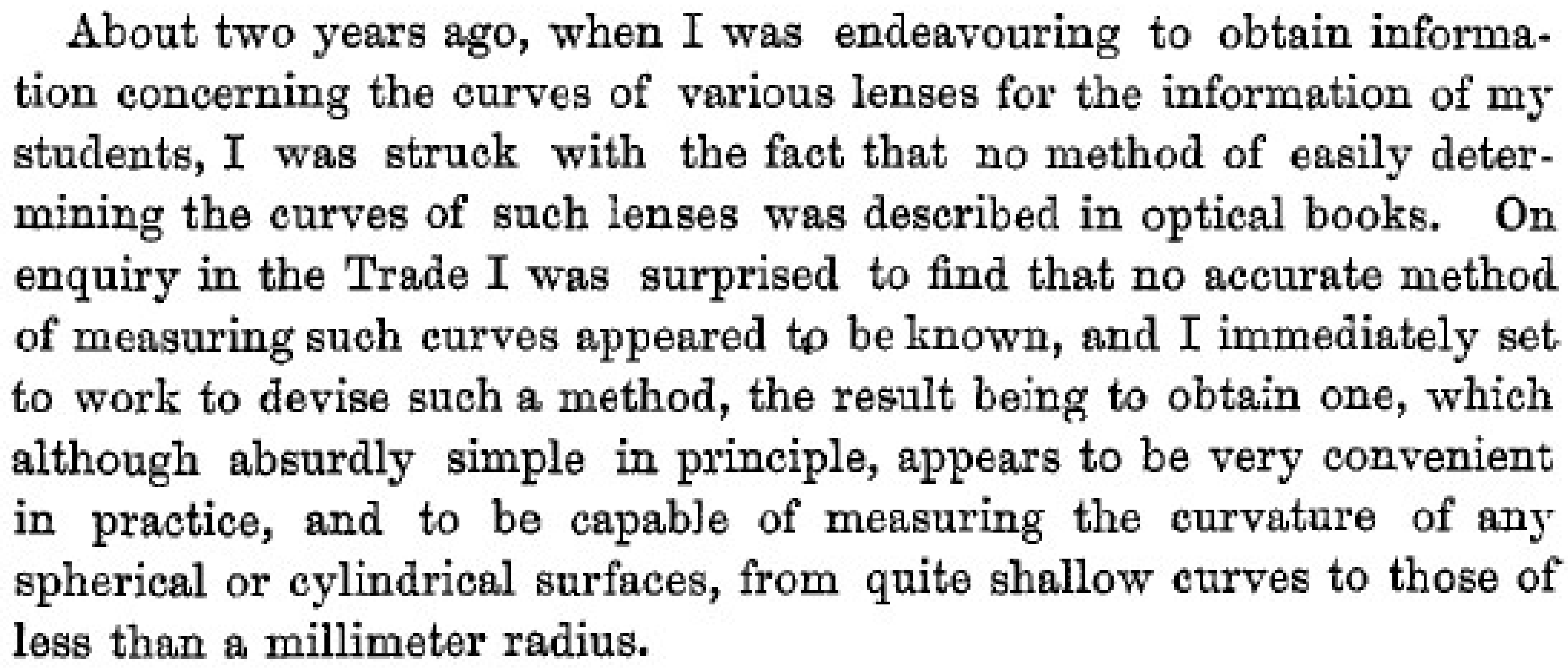
Outline

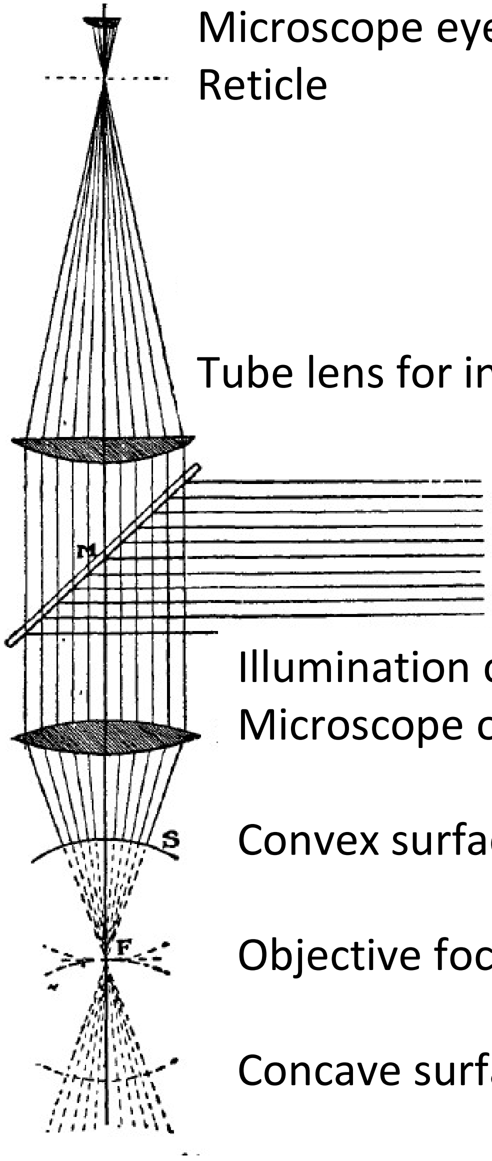
- What is an autostigmatic microscope (ASM)
- Measuring the radius of curvature of a concave surface
  - – Main historical use
- Modern version of an ASM uses internal infinite conjugate optics
- Use of an ASM for alignment of optical systems
- Other uses of an ASM
- Conclusions

Description of an ASM

First description in English literature is Drysdale*, Trans. Opt. Soc. London*, 1900



About two years ago, when I was endeavouring to obtain information concerning the curves of various lenses for the information of my students, I was struck with the fact that no method of easily determining the curves of such lenses was described in optical books. On enquiry in the Trade I was surprised to find that no accurate method of measuring such curves appeared to be known, and I immediately set to work to devise such a method, the result being to obtain one, which although absurdly simple in principle, appears to be very convenient in practice, and to be capable of measuring the curvature of any spherical or cylindrical surfaces, from quite shallow curves to those of less than a millimeter radius.



Microscope eyepiece

Reticle

Fig. 2 from the Drysdale paper of 1900

Tube lens for infinite conjugate microscope

Illumination coming from an infinite source

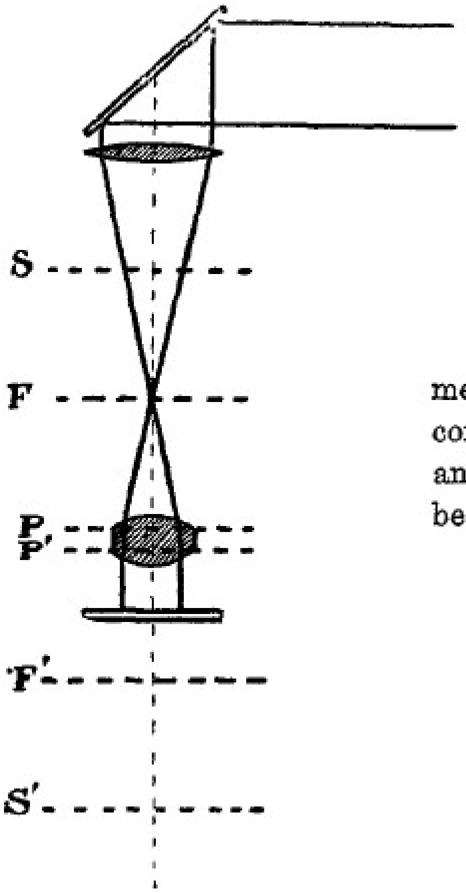
Microscope objective (infinite conjugate type)

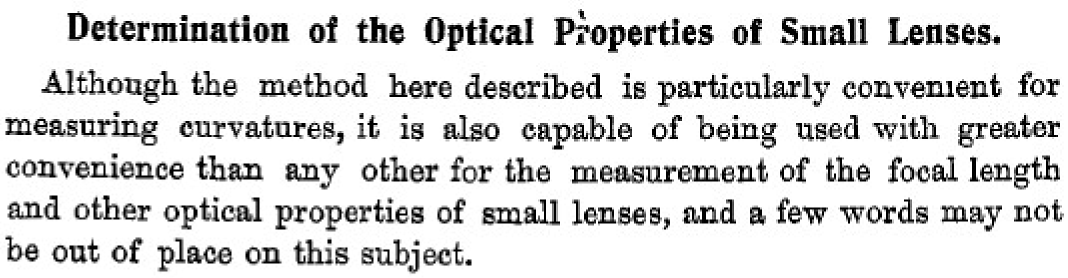
Convex surface with center of curvature at objective focus

Objective focus and concave/convex surface shifted to focus

Concave surface with center of curvature at objective focus

Further from the Drysdale paper





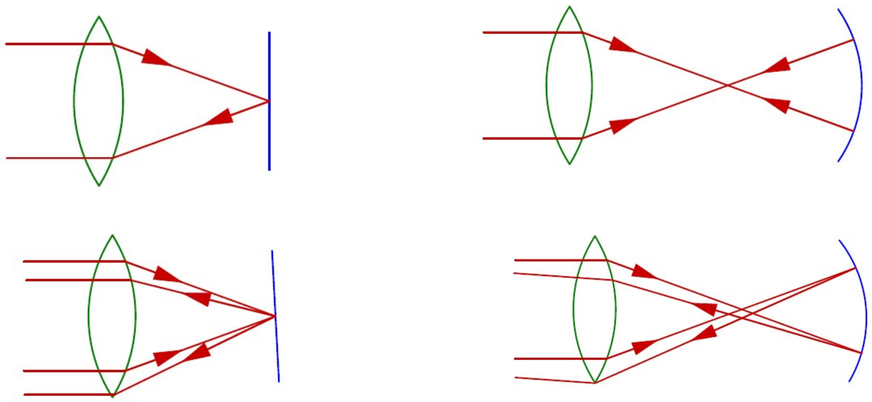
Determination of the Optical Properties of Small Lenses.

Although the method here described is particularly convenient for measuring curvatures, it is also capable of being used with greater convenience than any other for the measurement of the focal length and other optical properties of small lenses, and a few words may not be out of place on this subject.

Cat’s eye and confocal foci

Surface normal to ASM axis
or surface C of C at ASM focus

Surface tilted to ASM axis or
ASM focus displaced from
C of C of surface



Cat’s eye reflection

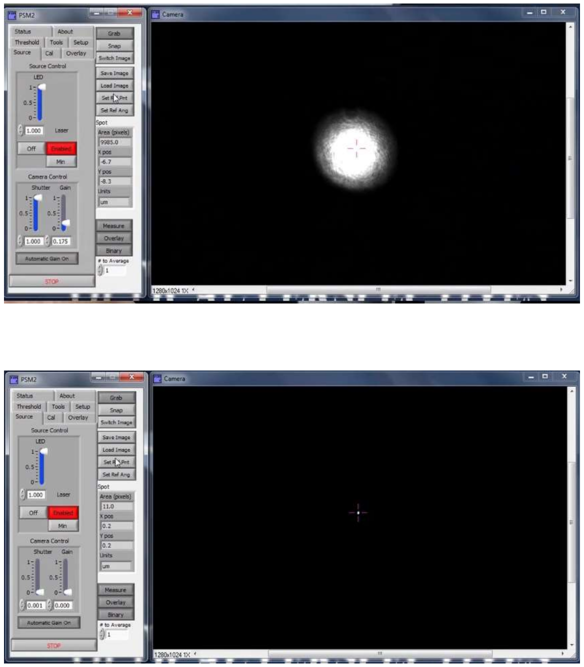
Objective focused on surface
curvature
Out going rays re-enter on opposite
side of objective
If surface tilted, reflected rays parallel
outgoing rays in collimated space
Cat’s eye used for setting crosshairs
Cat’s eye used for setting reference

Confocal reflection

Rays focused at center of

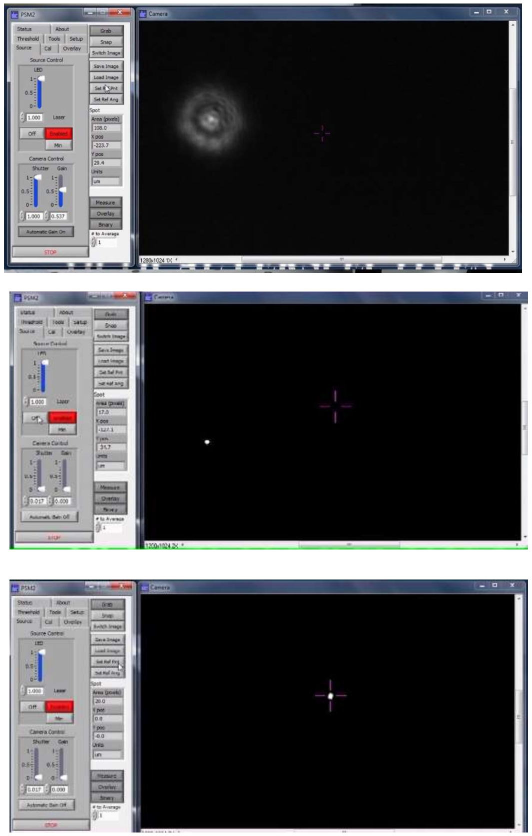
Rays hit surface at near normal
incidence and re-trace themselves
If surface tilted, rays do not re-trace
and will not center on crosshairs
Confocal used for alignment
Confocal for bringing CofC to reference

Examples of Cat’s eye and CofC spot images



Out of focus Cat’s eye spot image (above)
In focus Cat’s eye (below)
Notice Shutter and Gain with focus

Locate an ephemeral point in space with 3 degrees of freedom to µm precision



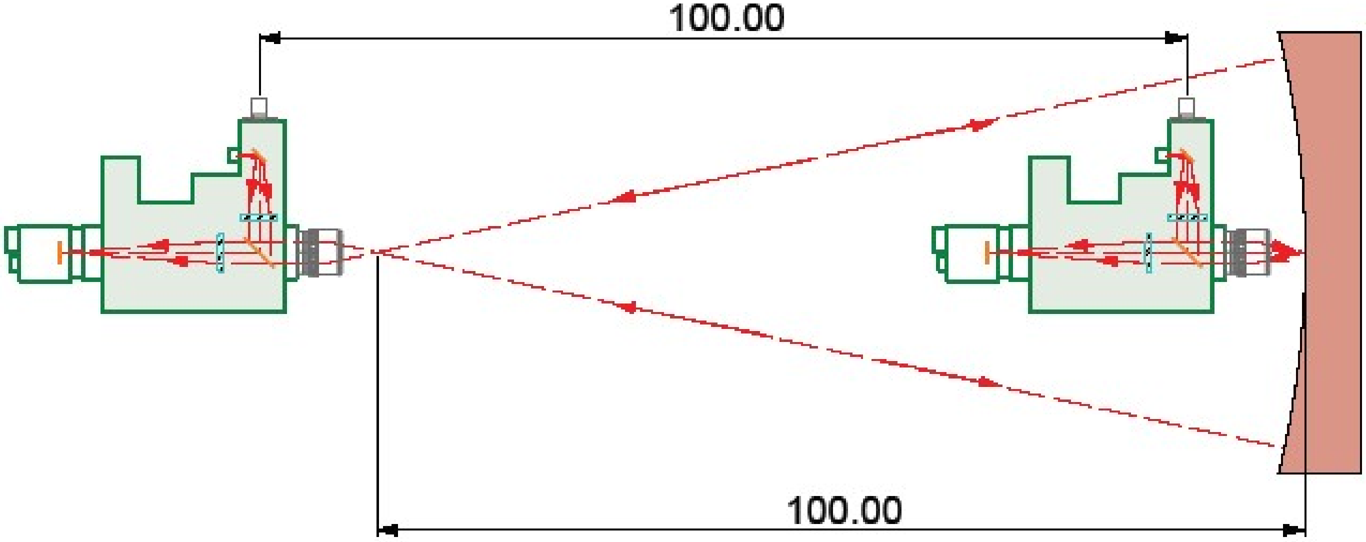
Out of focus & decentered CofC spot
In focus but decentered CofC spot
In focus and centered CofC spot

Measurement of radius of curvature

Consists of three steps:

1. Focus on the concave mirror surface to get a Cat’s eye reflection
   Set the reticle or electronic cross hairs on the reflected point image
   This established the optical axis of the ASM
2. Move the ASM back to near the center of curvature of the concave mirror
   Locate the reflected focused spot which may not be aligned to the objective
   Tilt the mirror until the reflected focused spot enters the objective
   Focus the ASM on the reflected spot and center it on the crosshairs
   Note the distance of the ASM on a linear scale
3. Move the ASM forward until it is focused on the mirror surface
   Moving from center of curvature means moving on a normal to the surface
   Get a sharp focus the Cat’s eye reflection
   Cat’s eye reflection will necessarily be centered on the cross hairs
   Read the distance of the ASM on the linear scale
   The difference of the Cat’s eye and confocal positions is the radius of curvature of the mirror

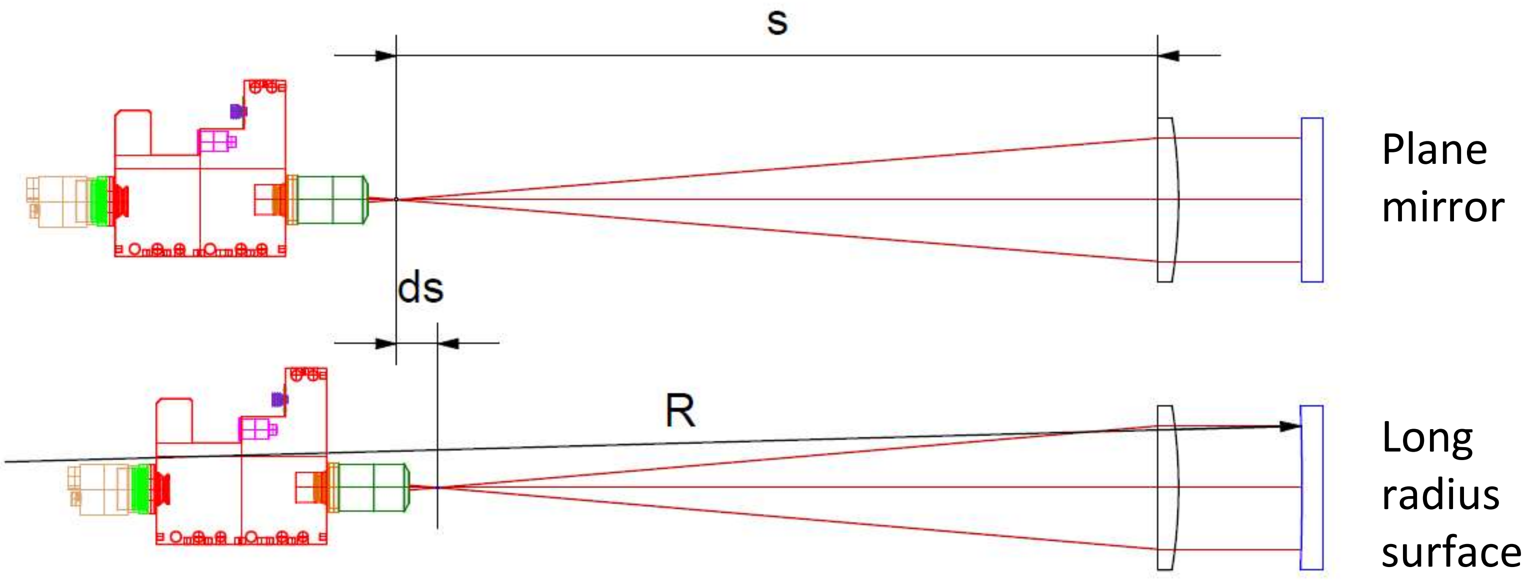
Measurement of radius of curvature



1. Focus on surface, used Cat’s eye reflection to set crosshairs
2. Move to confocal, adjust microscope so reflected spot in focus and centered on crosshairs, note linear scale reading
3. Move to focus on surface and get well focused Cat’s eye spot. Note scale reading Difference in readings is the radius of curvature

If this concept is well understood all other applications are easy

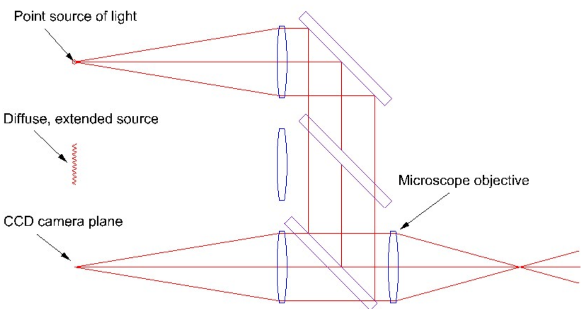
Measurement of long radius of curvature
Use defocused collimator

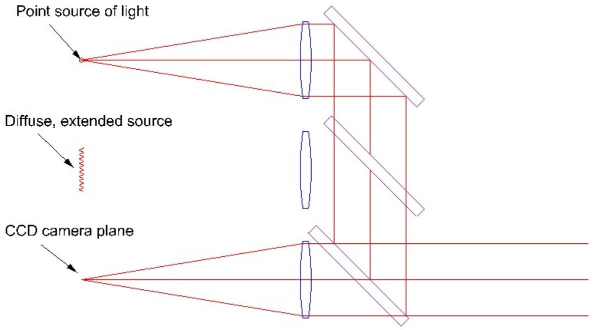


1. Find s by putting a plane mirror in front of collimator
2. Put long radius surface in front of collimator and note ds
3. Since to first order efl = s, 1/s = 1/(s – ds) + 1/R, we find R = -s(1 + (s/ds))

(Be careful of signs, use common sense)

A contemporary version of the ASM is three instruments in one



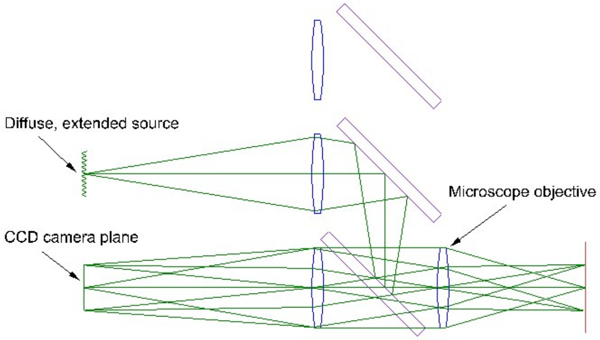


Autostigmatic microscope

Internal SM fiber source

Electronic autocollimator

Simply remove objective



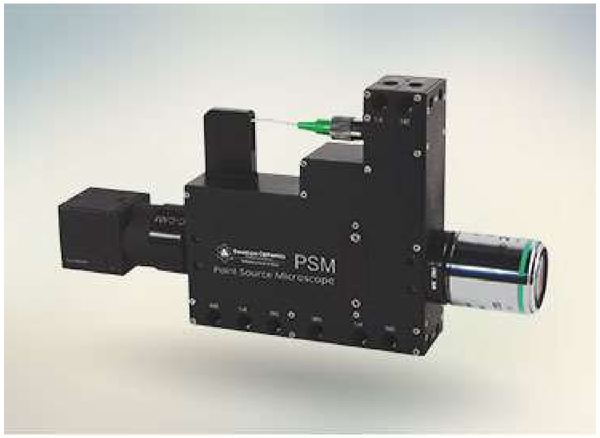
Video imaging microscope

Image plane parafocal with ASM focus

Internal LED Kohler source

Some advantages of the contemporary design

- Use of solid state light sources – compact, internal, low heat, monochromatic
- SM fiber coupled laser diode – bright for ease of alignment, near perfect spot
- Video camera – ergonomic, high position sensitivity, settable reference
- Software – permits high resolution centroiding on reflected spot
  - Large dynamic range on reflected light intensities
  - Recording and storage of Star images for optical quality determination
  - Centroid data easily coupled into other scales, a CMM, for example



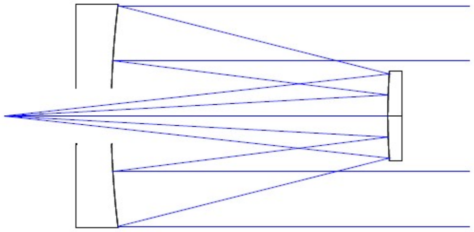
Other uses of the ASM; designed for alignment

Perfect for locating centers of curvature and foci of optical systems

- Use as a sensor on a centering station using a rotary table to define an axis

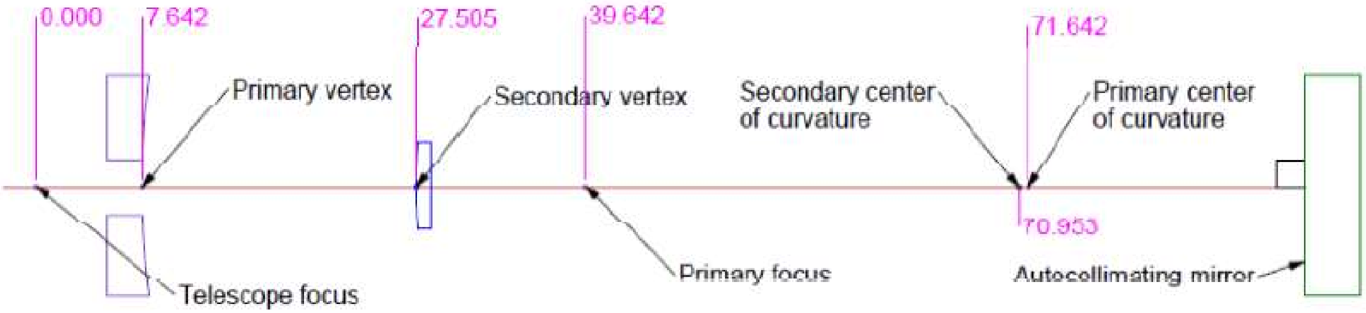
Use was to align the elements of a f-theta laser scanner lens to a common axis

- Lens system had spherical and toroidal lenses and an "off-axis" mirror
- ASM mounted to the ram of a coordinate measuring machine
- Used as a large x, y, z stage to pick up centers of curvature and align to axis

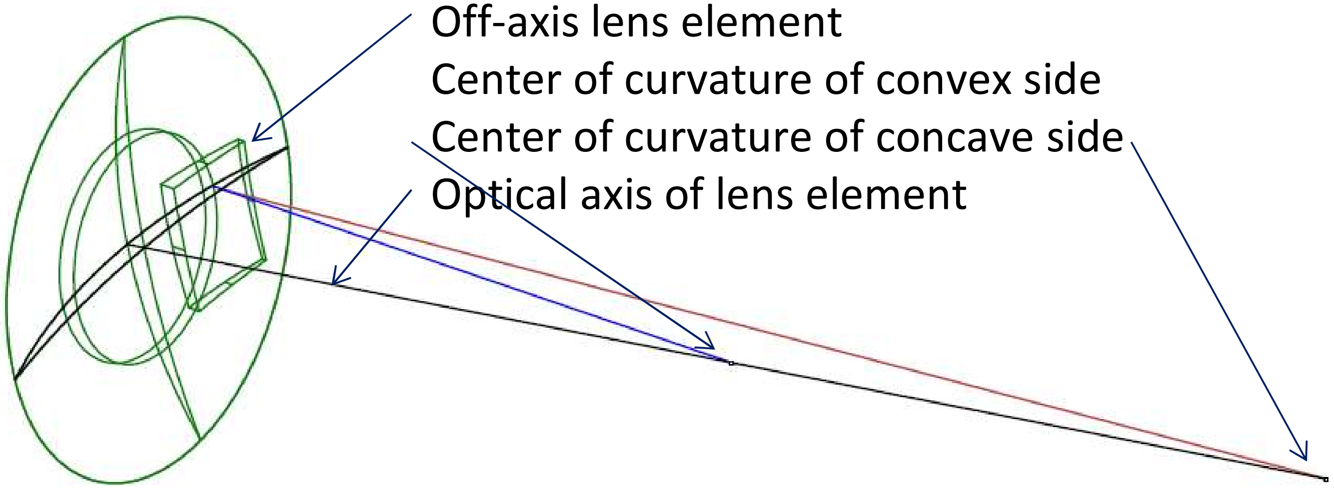


Don't think like a lens designer and where rays go

Think about where centers of curvature should go and how to get them on a common axis



Use two ASM’s to align an “off-axis” lens



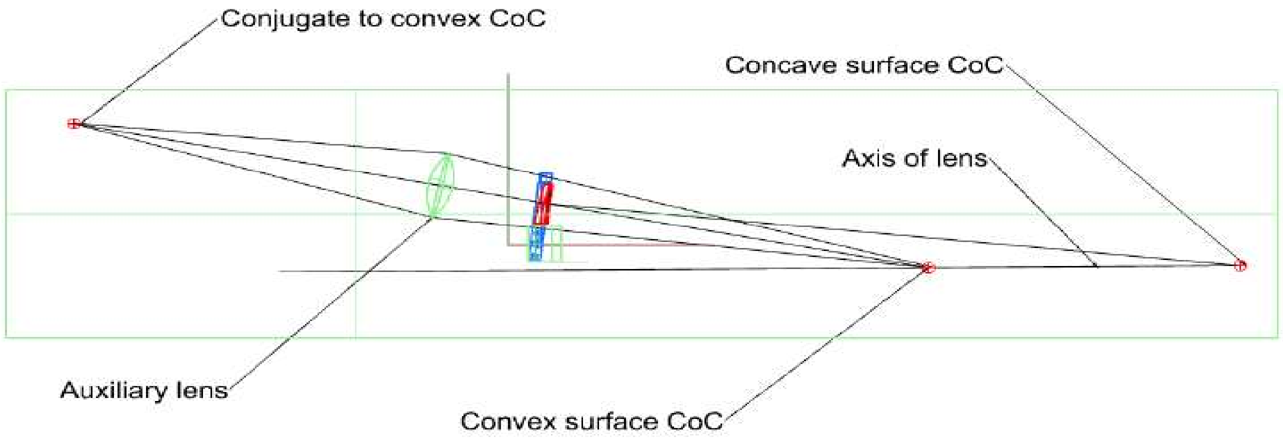
Off-axis lens element

Center of curvature of convex side

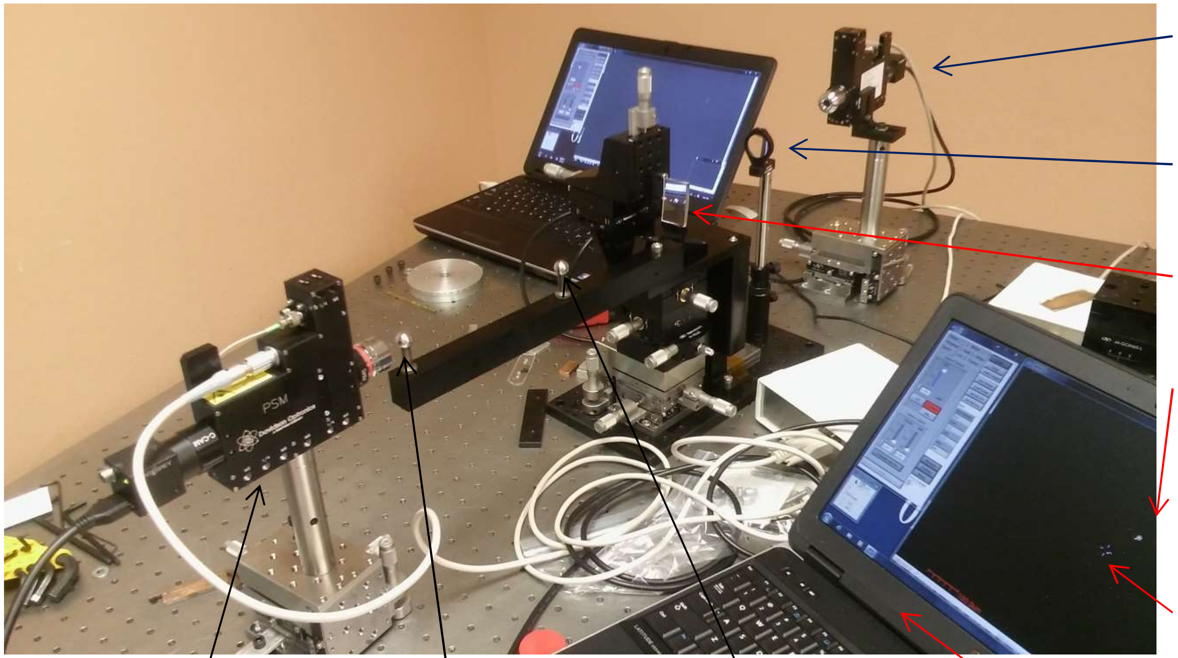
Center of curvature of concave side

Optical axis of lens element

Radius of convex side longer than working distance of objective, need extra lens



Set-up using 2 ASM's to align lens



First PSM

Auxiliary lens

"Off-axis" lens

Return spot from ball

Crosshairs

Second PSM

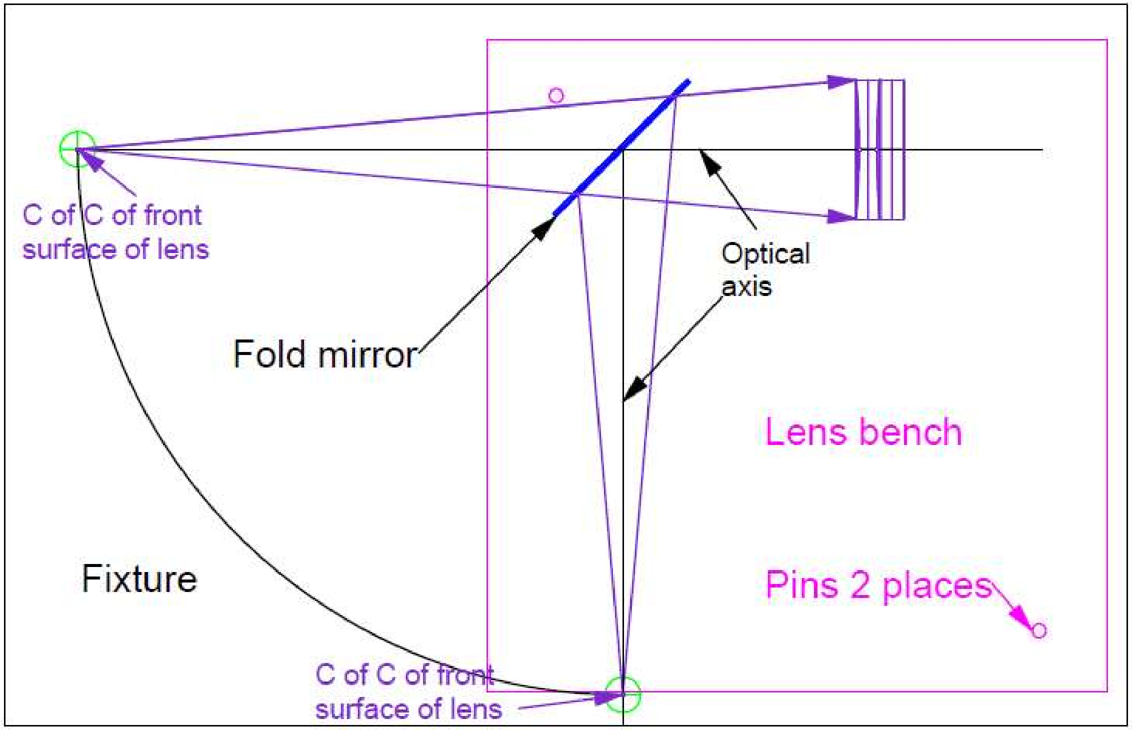
Ball at CC CofC

Ball at CX CofC

Laptop for 2nd PSM

Once set up the alignment took a couple of minutes
Time savings in production would be immense

Alignment of fold mirrors

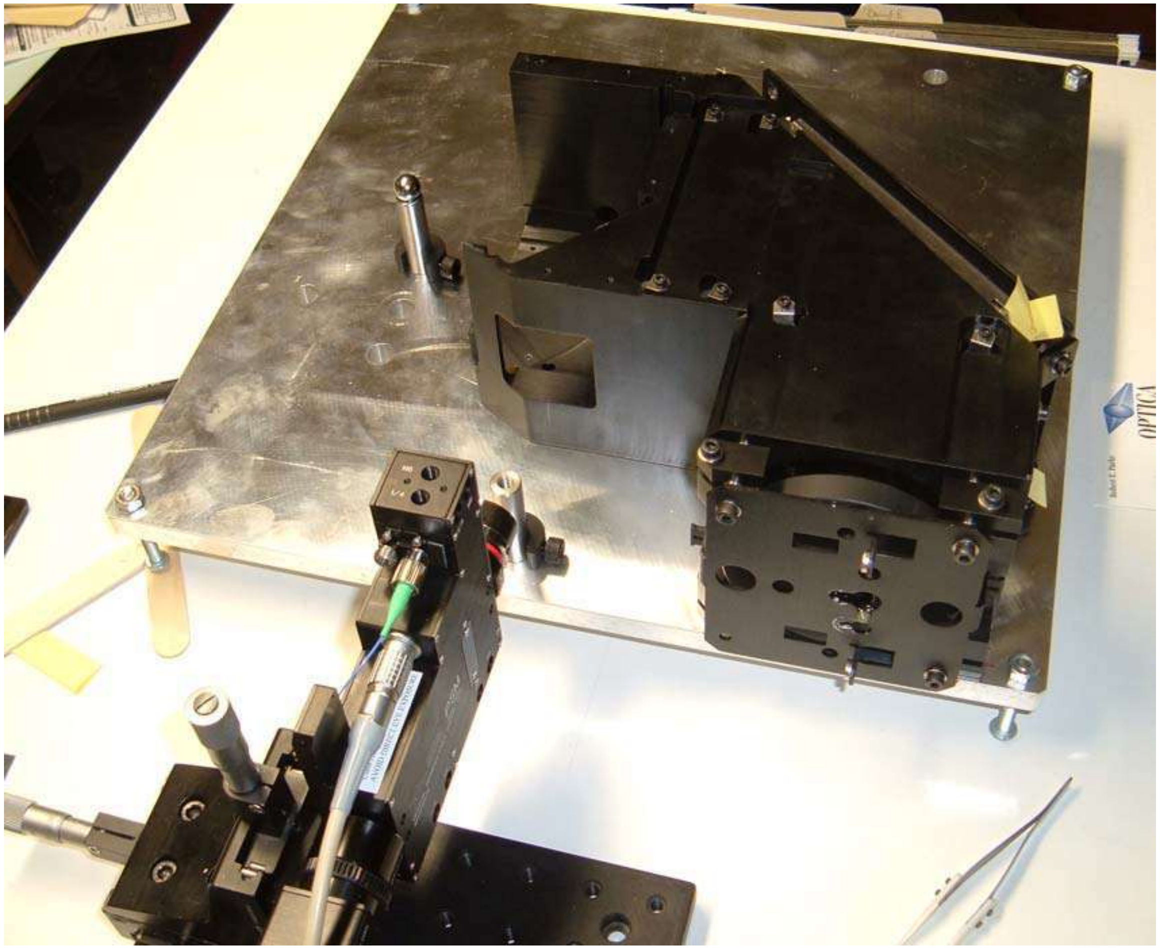


Plane fold mirrors have 3 degrees of freedom, 2 tilt and one displacement

Optical and mechanical design will show where the center of curvature should be located when the fold mirror is proper aligned

A ball in a fixture will mechanically locate this position, and ASM can verify

Another example of a fixture for alignment



The role of steel balls in alignment

Steel balls are a physical realization of a point in space

Something you can physically touch as opposed to a theoretical object

The ball center, the “point”, defines 3 translational degrees of freedom in space

The ASM transfers an optical point, a CofC or focus, something you cannot touch,

to the center of a ball, something that can be located physically

Steel balls are inexpensive, extremely precise and come in many sizes

Grade 5 chrome steel balls are round to 125 nm and cost about $3 each

Can be thought of as convex optical grade mirrors

Plug gauges are the cylindrical equivalent of balls and define axes in 3 DofF

(Plug gauges are Go/no go pins for gauging the size of holes)

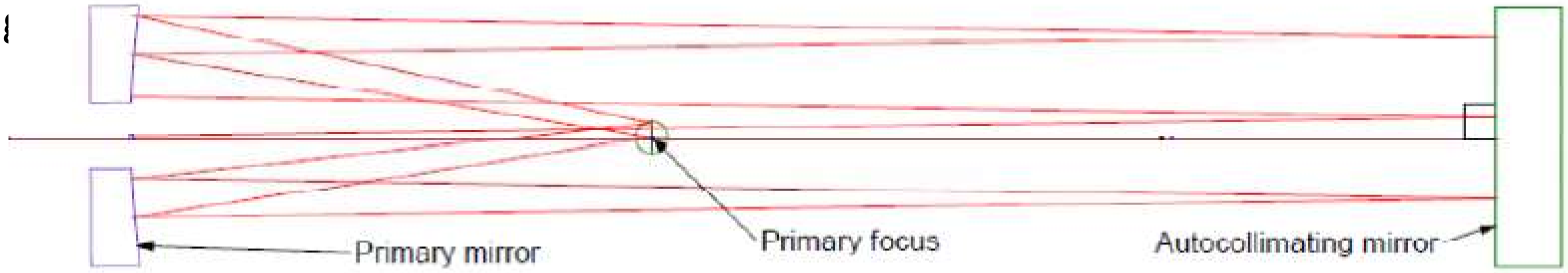
Alignment using aberrations

An ASM is a “Star” test device showing the point spread of an aberrated wavefront

It has sensitivity to about lambda/8 or lambda/10

Useful for quick check of quality of optical surfaces as they are assembled into systems

Ali



Initially the return spot will not be centered on the crosshairs of the ASM

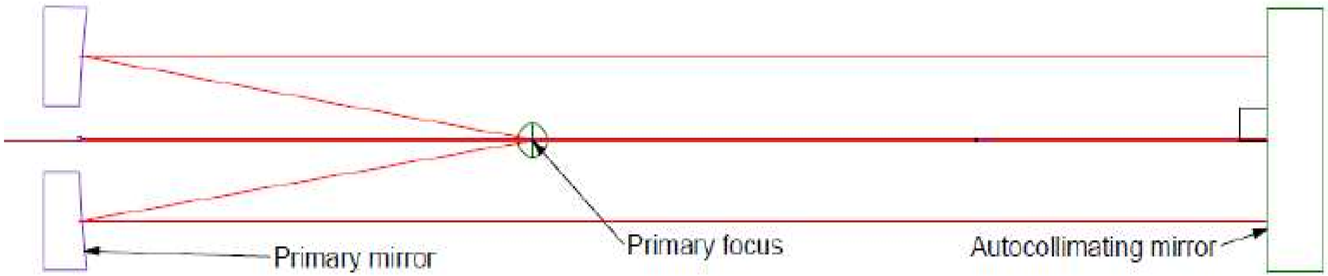
The parabola or autocollimating mirror are tilted until return spot on crosshairs

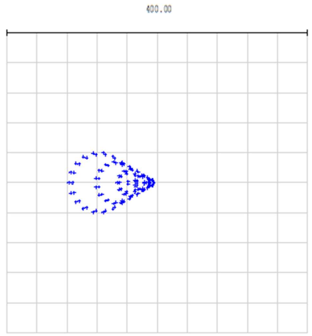
Alignment using aberrations (con’t)

When return spot lies on the crosshairs, the rays strike the flat at normal incidence

However, the normal to the flat may not be parallel to axis of parabola

As a consequence, the return spot will show coma



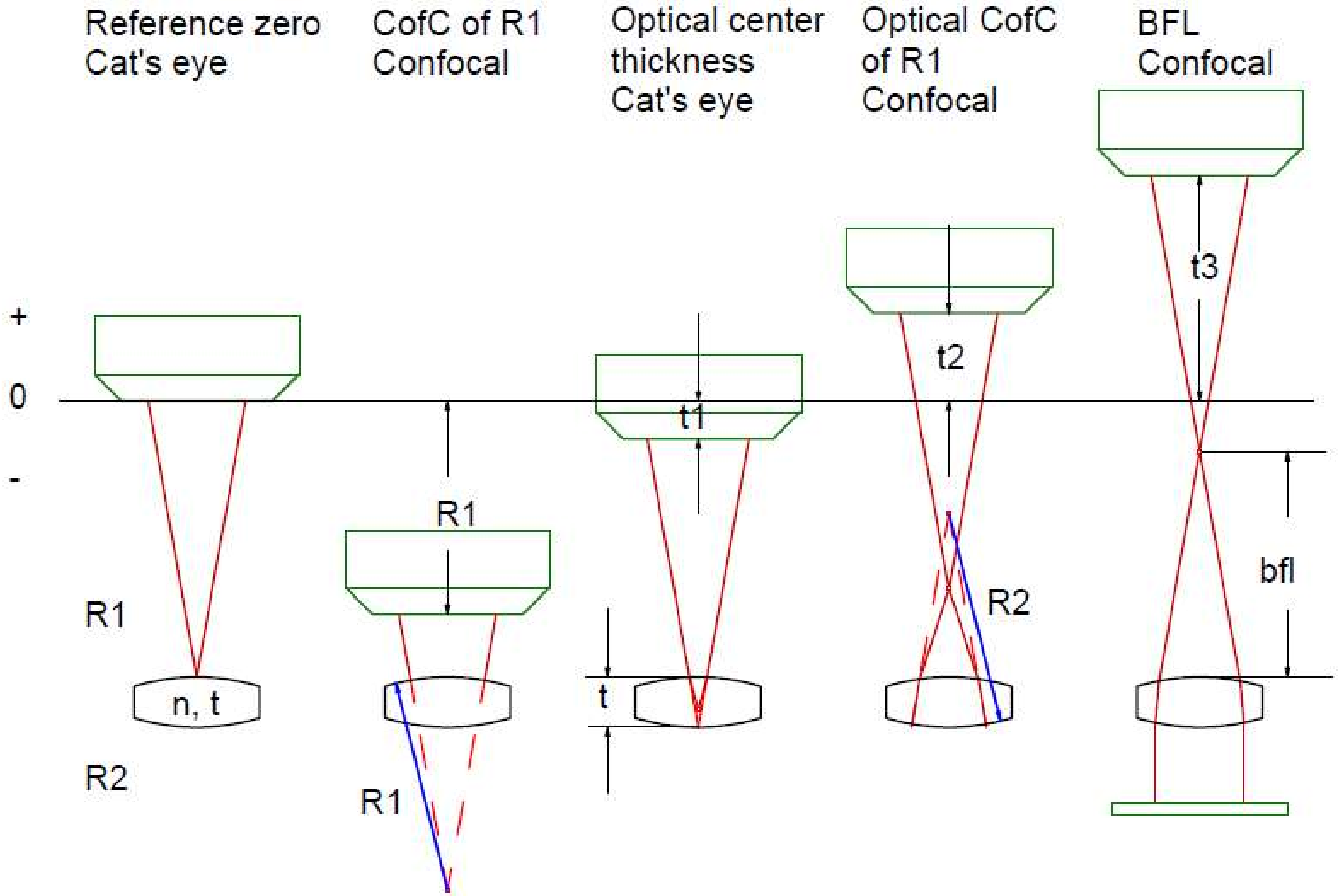


Simulated point spread of coma

To finish the alignment, tilt the flat while keeping return spot on the crosshairs until the coma is reduced to a symmetrical spot.

The entire alignment process takes only minutes to accomplish

Other uses of an ASM – Finding lens conjugates



Finding first order lens conjugates

Finding the radius of curvature of one side is direct measurement

This assumes it is concave or there is sufficient working distance

Almost any lens can be reversed and measured through the opposite side if not enough working distance

To find the other conjugates it is necessary to model with a lens design program

Or use first order equations and an iterative equation solving program

See Parks, R. E., “Measuring the four paraxial…, *Appl. Opts*., **54**, 9284 (2015)

Zero index material – a useful trick

When using an ASM or an interferometer most setups are double pass

Light comes from the instrument, reflects at normal incidence off the last surface and retraces itself back into the instrument

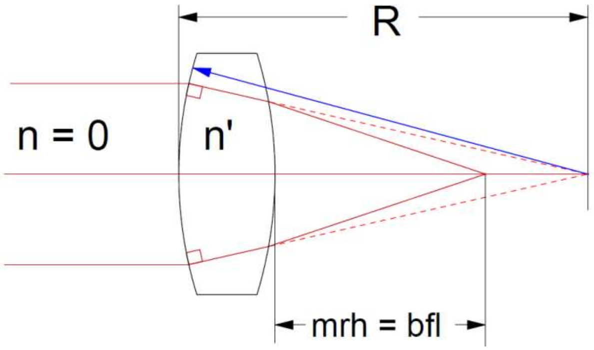
For a quick insight to the test it is a lot of work to trace a double pass system

The trick; reverse the system and make rays leave the last surface at normal incidence

To do this have rays from infinity travel through a medium of 0 index to the last surface

Then n*sin(θ) = n'*sin(θ') = 0, so θ' = 0, or the rays leave the last surface normal to it!

Now a marginal ray height solve after the last refraction shows the paraxial focus

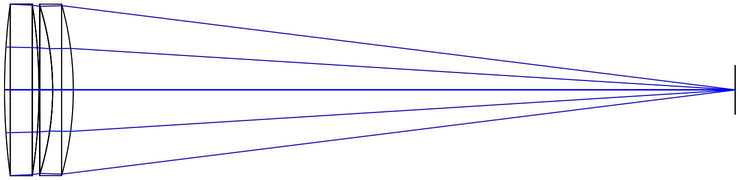


Credit for the idea; I don't know who deserves it
I learned it from Jim Burge at UofA, Optical Sciences
I suspect he may have learned it from Roland Shack
If someone knows a better attribution I like to know.

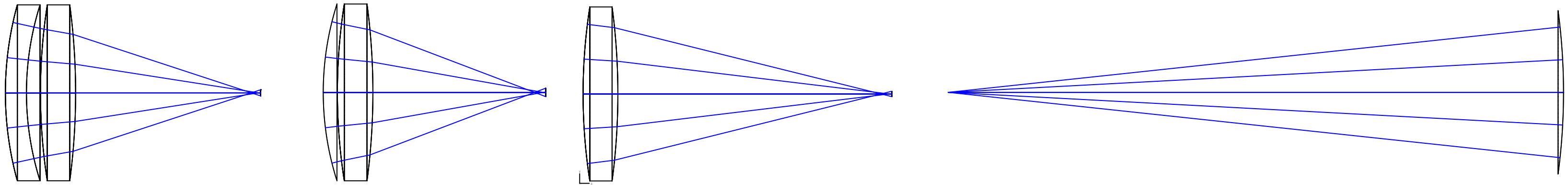
An example – finding CofC’s and surfaces

Assume a simple optical system such as an air spaced doublet

Find the centers of curvature and surfaces vertices looking into the system



Reverse elements, object at infinity and n = 0, float by stop on last surface



MRH = 26.403 = 24.395 = 39.445 = -94.453

Object on first surface, image space f/# large, stop on last surface

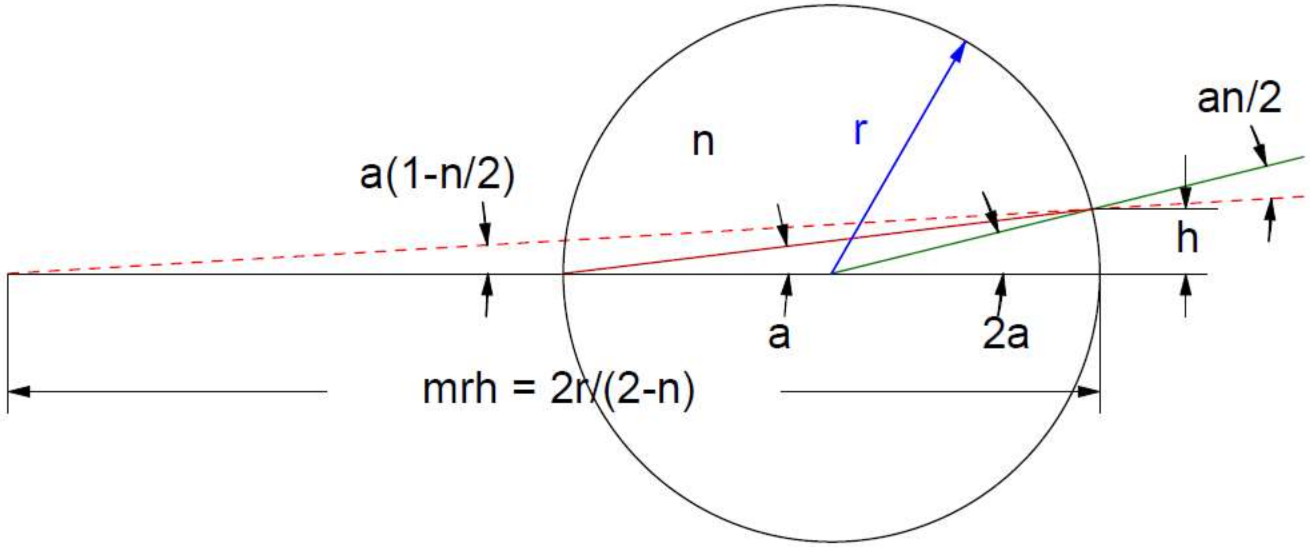
MRH = -7.471 = -5.492 = -3.368 = 0

Find the index of refraction of a ball

For small angles a = h/2r, and the normal = 2a, so the refracted ray angle is an/2

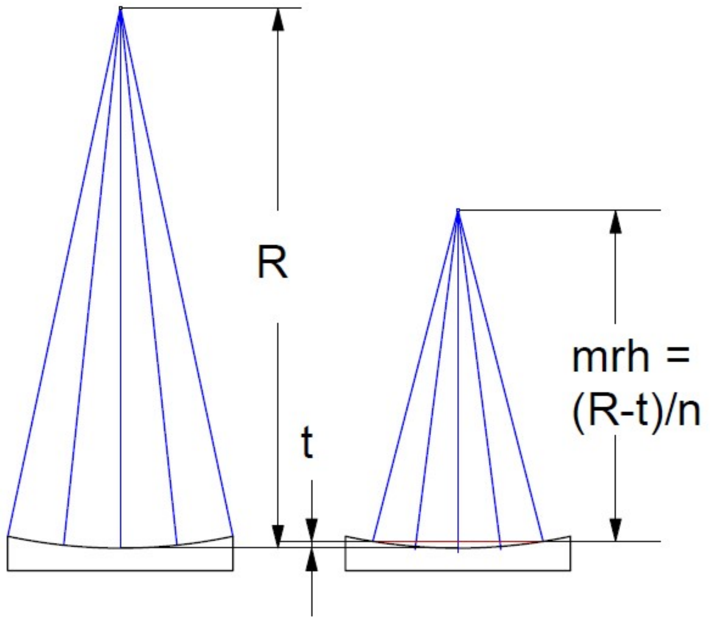
The ray angle relative to the x axis is 2a – an/2 = a(1-n/2)

The mrh = h/(h/r(1-n/2)) = 2r/(2-n)

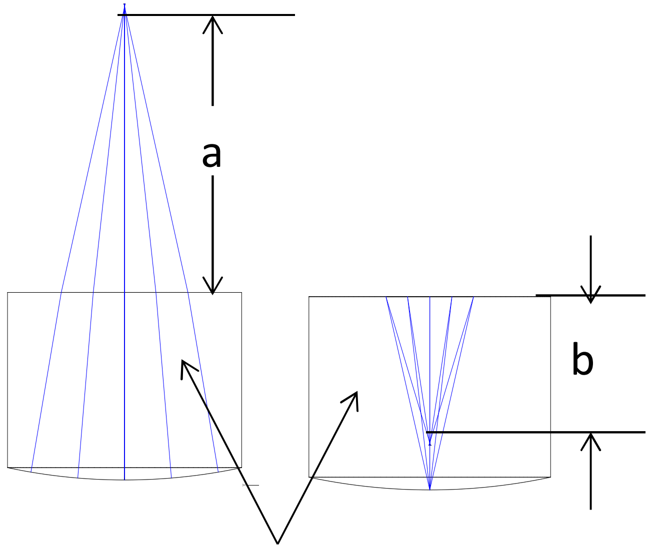


Or, n = 2(mrh – r)/mrh
Works even if ball behind a window in a thermal chamber, but use ray trace

Find the index of a liquid and radius of a submerged surface

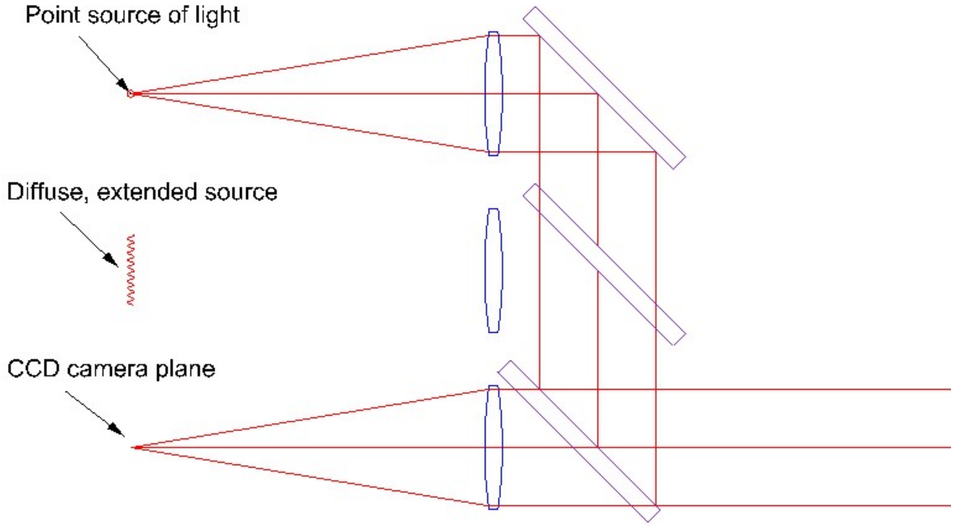


Concave mirror with radius R, left
Mirror with liquid index n, right
n = (R – t)/mrh, t = liquid thickness
Liquid is plano-convex lens



Liquid of index n, must be known
Measure a and b relative surface of liquid
The liquid thickness t = b*n,
and a = (R/n) – b, so R = (a + b)*n

Measurement of angle



As shown earlier, by simply removing the objective the ASM is an autocollimator with sub-arc second sensitivity

The bright mode of the laser source makes initial alignment easy in ambient light

The small beam size makes it particularly useful for inspecting small prisms

ASM’s and computer generated holograms

A CGH pattern can simulate a ball, that is focus light a specific distance above the CGH

If balls are used to kinematically locate a CGH, a pattern to locate the balls can be included as part of the overall pattern. Then an ASM can precisely locate the balls. The balls, cemented in place, become an integral part of the CGH test artifact.

Because a CGH pattern can simulate a ball, a CGH can be made as an artifact for locating a group of points in space precisely located to < 1 µm in 3 dimensions.

An ASM mounted on a robot arm, for example, could be used to pick up the points one at a time to train and calibrate the robot.

Example of CGH hologram

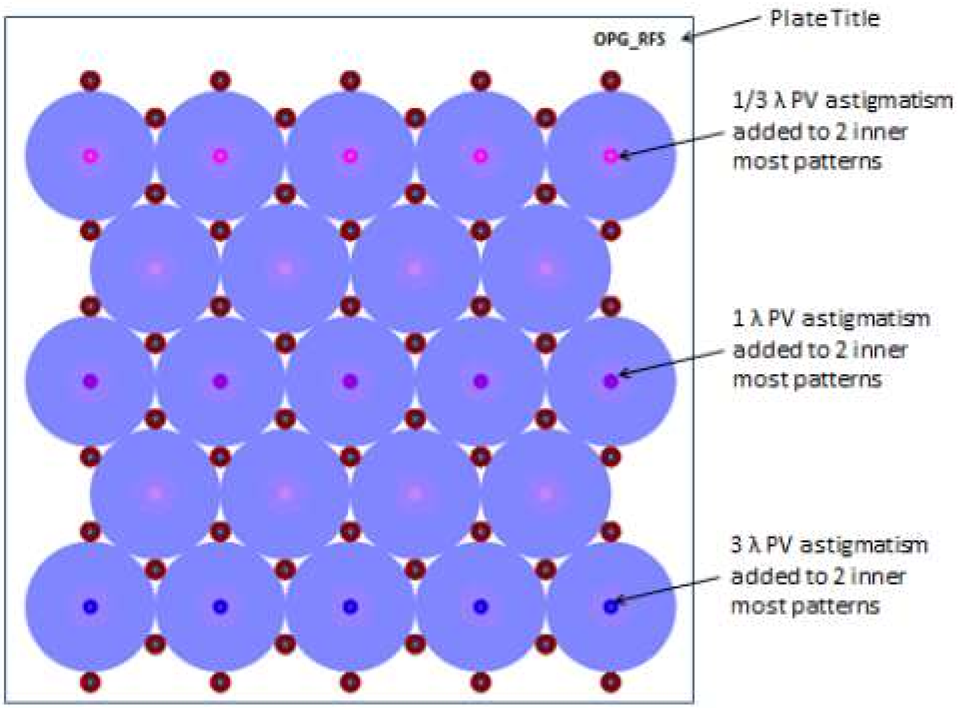


Plate Title

1/3 λ PV astigmatism added to 2 inner most patterns

1 λ PV astigmatism added to 2 inner most patterns

3 λ PV astigmatism added to 2 inner most patterns

Printed on a 150 mm square photomask substrate
Each circular pattern produces points several distances above the CGH
Actual photograph is not available at the moment
CGH courtesy of Arizona Optical Metrology, LLC, www.cghnulls.com

Conclusions

While autostigmatic microscopes (ASM) are over 100 years old, modern technology makes them truly practical for many diverse optical metrology needs.

Once the basic operation of measuring the radius of curvature with an ASM is understood, it becomes obvious that an ASM has many more useful applications.

Almost everything discussed here can also be done with an interferometer with greater precision. However, if the ultimate in precision is not needed the ASM is more convenient to use because of its small size, light weight and ease of mounting. Further, in some applications the greater coherence of an interferometer make some of the applications more difficult to perform because of multiple fringe patterns.

In many instances an ASM is a cost effective and easy to use alternative to an interferometer.