Alignment

OPTI 415-515

Definition of alignment (1st part)

Placing the optical axis of each element on the optical axis of the system

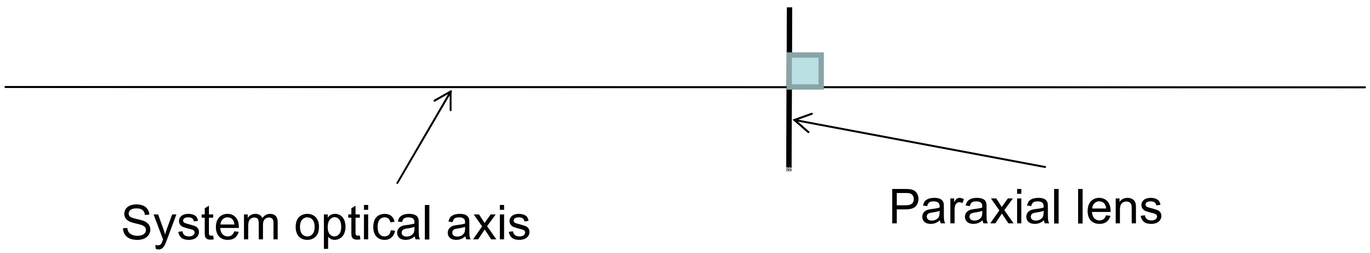
This implies defining the optical axis of the system and finding the optical axes of the elements

Also implies a means of defining the zero field position

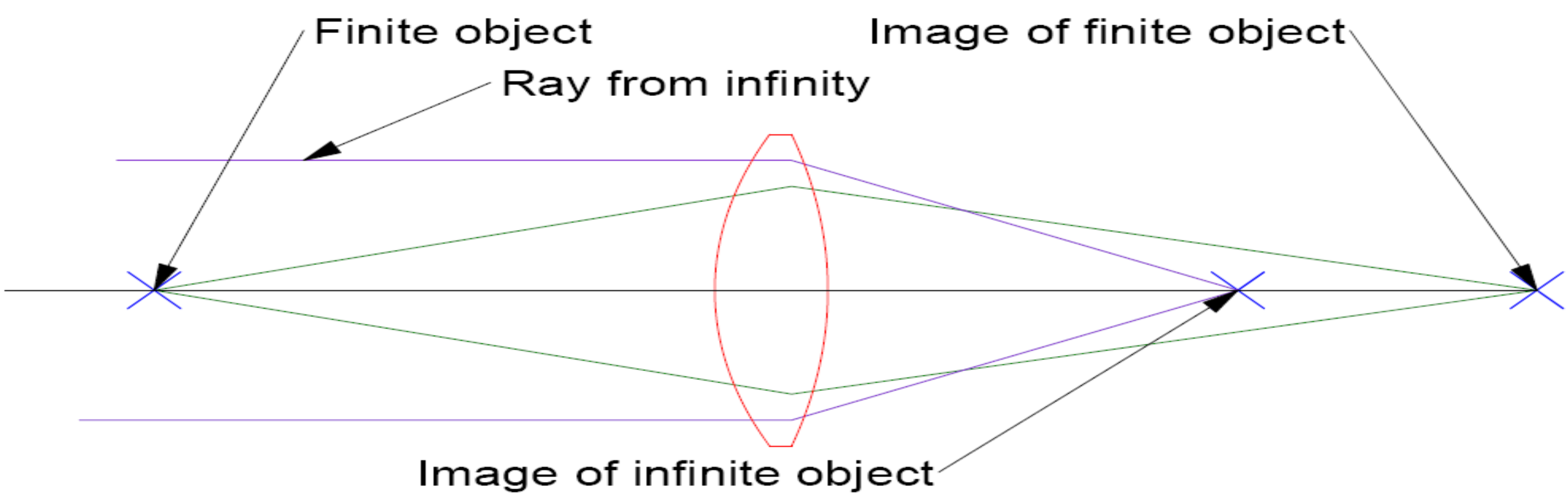
Model the system as a paraxial lens

The axis goes through the center of the lens and is perpendicular to the lens (a plane)

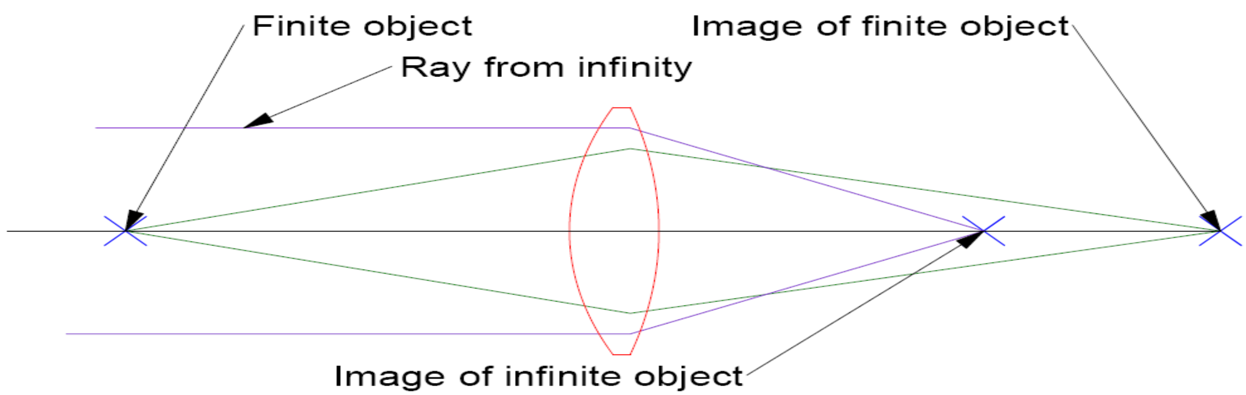
System optical axis



For zero field, object and image are on the axis



Implications of the definition



Line between object and image is undeviated going through lens

Ray must strike perpendicular to lens surface

Centers of curvature of lens are on optical axis

Ray normal to sphere goes through center of curvature

As a consequence, all centers of curvature must lie on the optical axis

(There are some asymmetric systems where this is not true)

Definition of alignment for a rotationally symmetric system

A system is aligned if the center-of-curvature of each element is positioned on the optical axis at its correct location.

Generalizations:

A surface can be a conic or a general aspheric surface if the center-of-curvature is thought of as a paraxial feature of such an element.

Similarly, the center-of-curvature can be for a specified zone (annular region).

Generalized definition of alignment

A system is aligned if the optical data of every surface is correctly positioned.

Explanation:

For a rotationally symmetric lens comprised of two spherical surfaces, the center-of-curvature of the two surfaces is the optical data for the element.

For a parabola it is the focus and axis direction.

For a hyperbola and ellipse it is the two foci.

The generalized definition applies for both rotationally and non-rotationally symmetric systems.

Motivation for alignment

Alignment is really a two step process -

A first order step to control object & image location and mag

A second step to zero out aberrations using remaining DoF

If only the first step is done, then light is focused at the correct location

but the image quality will be poor, in general

The second step must be done to eliminate aberrations due to

alignment while holding the first order properties constant

Now we will look at a few definitions of DoF of various optical elements

Then we'll look at some examples

Alignment properties of some elements

Point – 3 degrees of freedom, x, y, and z – an idealization

Ball – 3 degrees of freedom, x, y and z – a physical realization of a point

A spherical surface is also a physical realization of a point

Its edge add further constraints – usually beam footprint

Line – 4 degrees of freedom, $x_{1,}$ y_1, $x_{2,}$ $y_{2,}$ or point and 2 angles

– an idealization

Cylinder – 4 degrees of freedom – a physical realization of a line

Plane – 3 degrees of freedom defined by three non-colinear points

Optically realized by a plane mirror, 2 tilts and axial position

Asphere – 4 degrees of freedom because it has an axis

Non-rotationally symmetric parts add 1 DoF for clocking (orientation)

Full constraint of a parts location and orientation requirescontrol of 6 DoF

Alignment properties of elements

Point – theoretical construct – defined by 3 position coordinates, x, y, z, or three degrees of freedom

Ball or sphere – physical realization of a point

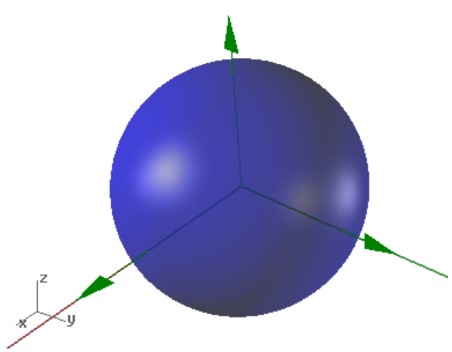
Defined by location of center, x, y, z and radius, r

The center is an intrinsic property of a sphere, the radius extrinsic

A sphere has no axis; repeat, no intrinsic axis

Spherical mirror – section of a ball – a center of curvature and a radius

There is <u>no</u> optical axis, only a mechanical axis



Alignment properties of elements, con't

Line – theoretical construct – defined by 2 points at arbitrary distances along the line, say, x1, y1 and x2, y2, or 1 point, x1, y1 and 2 angles, alpha and beta, or 4 degrees of freedom

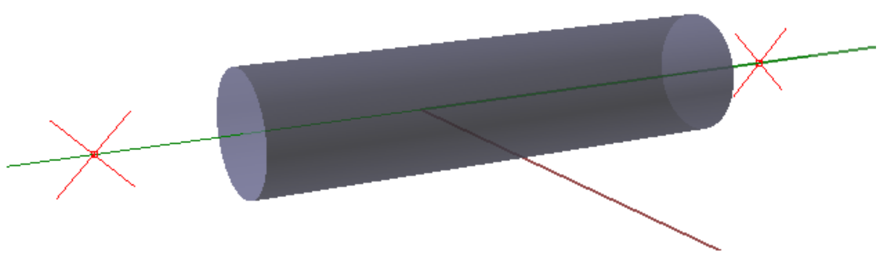
Cylinder or rod – is a physical realization defined by a pair of points or a point and a pair of angles plus a radius about the line or axis

Axis is intrinsic, radius extrinsic

Cylindrical mirror – defined by an axis or line and a radius

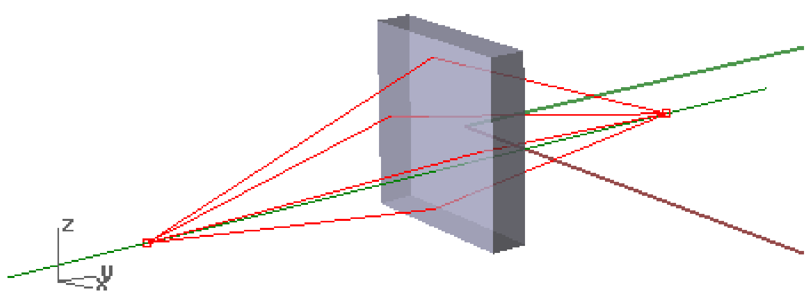
Edge add further constraints

Axis is intrinsic, and the radius extrinsic



Alignment properties of elements, con't

- Plane mirror – 2 degrees of freedom, 2 angles – intrinsic
  - Axial position is a degree of freedom but is arbitrary
- Virtual image defines a second point on the perpendicular to the mirror
- A single plane mirror cannot align a beam to an arbitrary new line of sight - insufficient degrees of freedom



Alignment properties of elements, con't

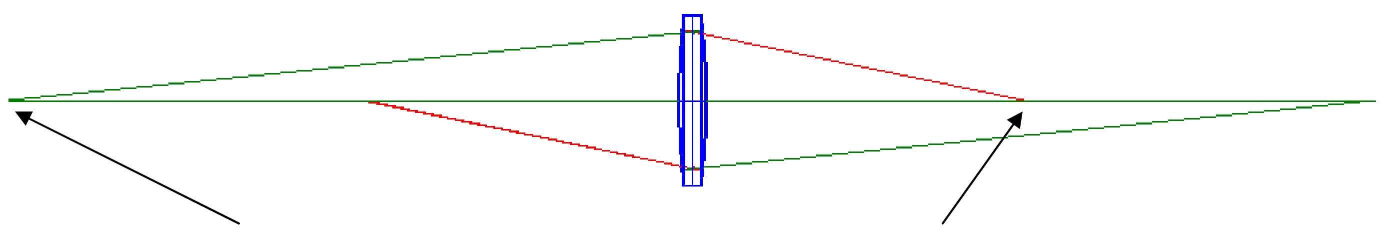
The axis of a lens is defined by the line joining the centers of curvature

This can be the physical CoC or the optically apparent CoC

There are four intrinsic degrees of freedom defined,

and extrinsic radii and thicknesses

Rotation about the optical axis is undefined



Physical center of curvature

Green lines

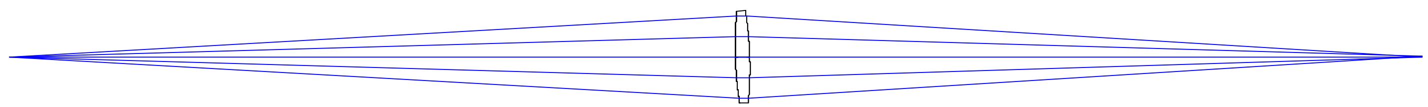
Optical center of curvature

Red lines

1:1 relay example of aberrations

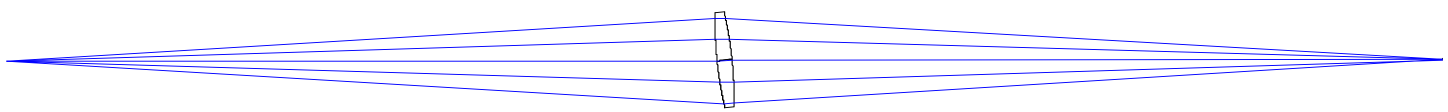
Biconvex lens with 100 mm efl used at 1:1 conjugates – Lab 1

If perfectly aligned and used at full aperture has 3.5 waves p-v of spherical aberration



If the lens is decentered just 2 μm we found the image moves 4 μm

To restore the image position the lens must be tilted almost 6 degrees and this introduces 10 waves p-v of astigmatism



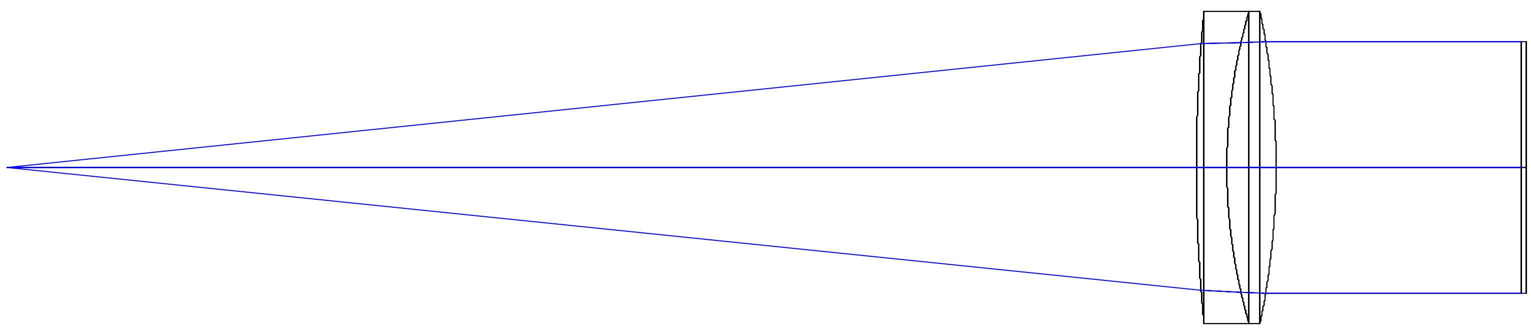
Physical CoC is 10 mm off-axis   Optical CoC is 4.8 mm off-axis

Holding CoC to 10 or 20 μm results in no aberrations

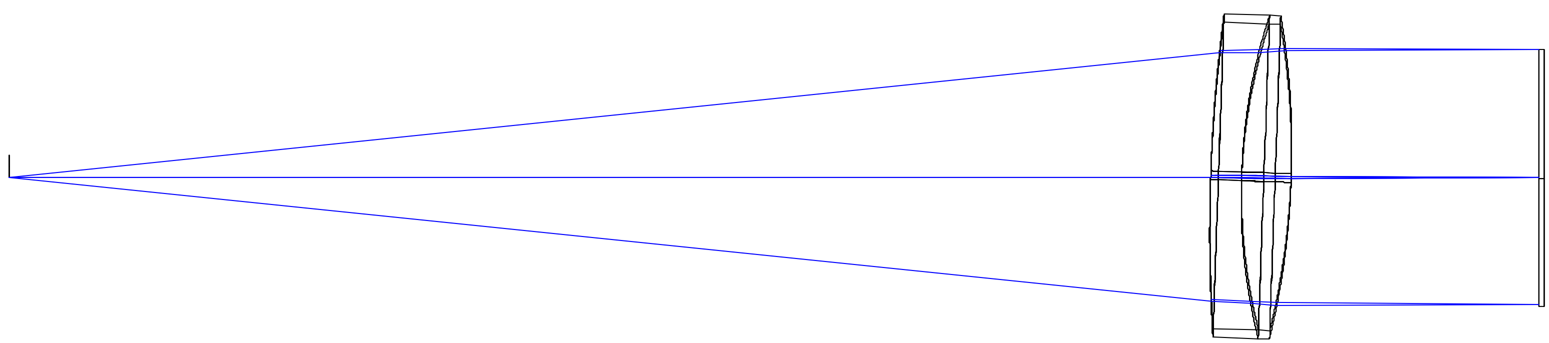
f/5 objective in autocollimation

100 mm efl achromatic objective in autocollimation off a plane mirror

If perfectly aligned the reflected wavefront is .6 waves p-v SA3 mostly



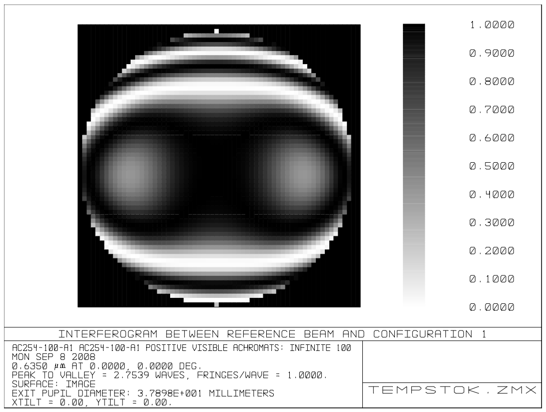
Tilt about 2 ° and decenter lens to keep image on top of object ~.34 mm

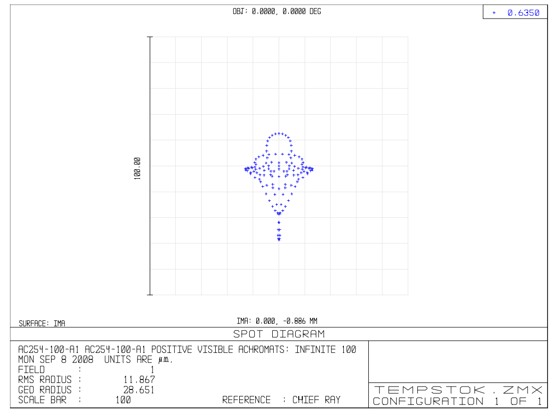


f/5 objective, con’t

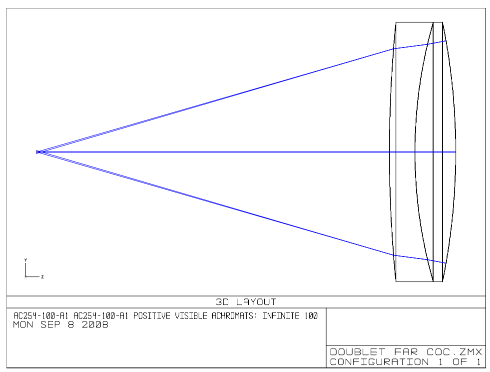
Now 2.75 waves p-v, mostly astigmatism, an off-axis aberration

Physical CoC are off axis by 4.4 and 2.2 mm

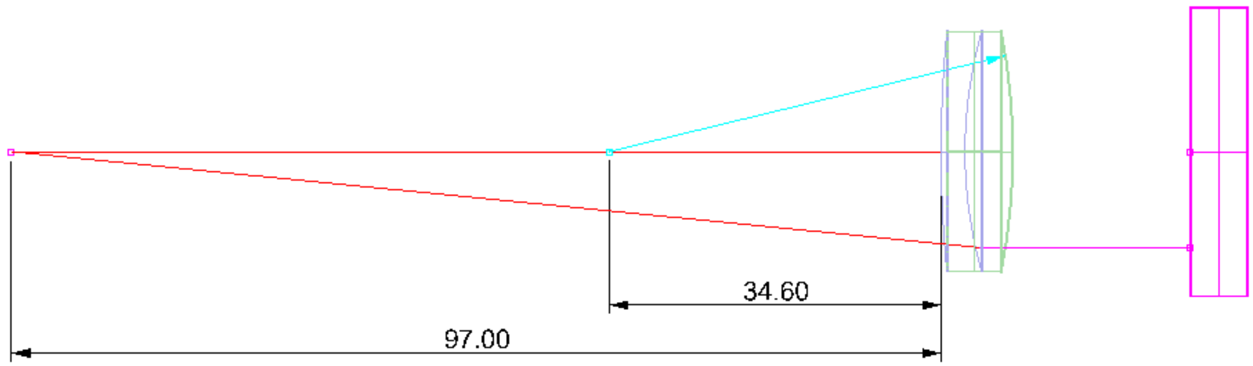




Distance from focus to vertex is 34.6 mm



Alignment of objective



Insert lens in front of plane mirror

Find autocollimated image, reflection from far surface of lens

Adjust tilt and decenter of lens, and tilt of plane mirror until both image and far surface reflection are centered when PSM moved along straightedge

Plane mirror will be perpendicular to table top and straightedge, and lens used in center of field

Use alignment telescope

Alignment telescope works like PSM except it focuses along its axis

Its near focus is about .5 m in front of the objective, far at infinity

Return reflection is a set of concentric rings

X, y adjustments will have to be made with the hardware

The alignment telescope will adjust in angle

Tools used for alignment - Autocollimator

- Autocollimator – telescope focused at infinity
  - Barrel concentric with crosshair in eyepiece – reversal to check
  - An internally illuminated reticle in filar eyepiece
  - Only measures angles – rather small acceptance angle
    - Use bright source in eyepiece to help initial alignment
  - Generally used in comparison mode – two surfaces at once
    - Such as wedge in a window – be sure to include index in calculation

Nikon autocollimator

Tools used for alignment – Alignment telescope

- Alignment telescope – telescope focuses ~1m to infinity
  - Barrel concentric with crosshair in eyepiece
  - An internally illuminated reticle or reticle on front element
  - Establishes a line of sight, images, measures lateral displacements

One knob to focus

Two dials move crosshair to

measure displacement

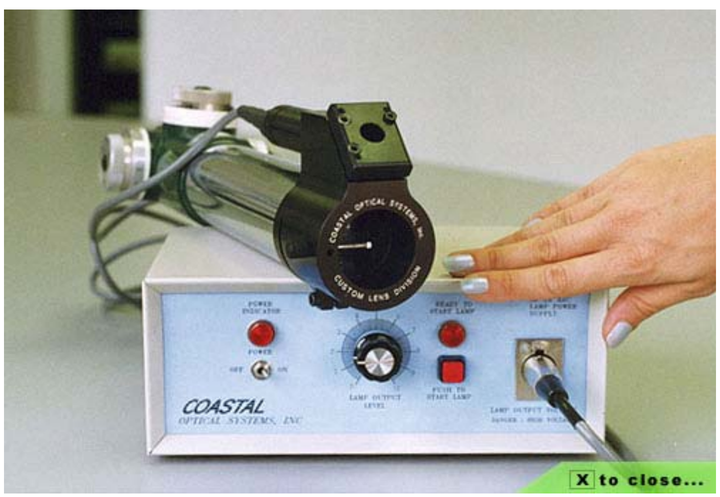
Straightness line of sight 50 um

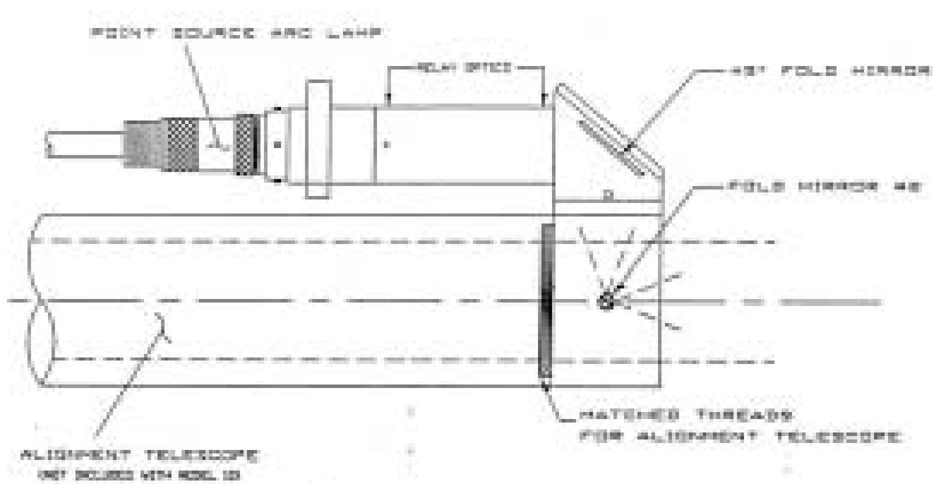
Rotate 180° for accurate setting

Photo from Brunson Instrument

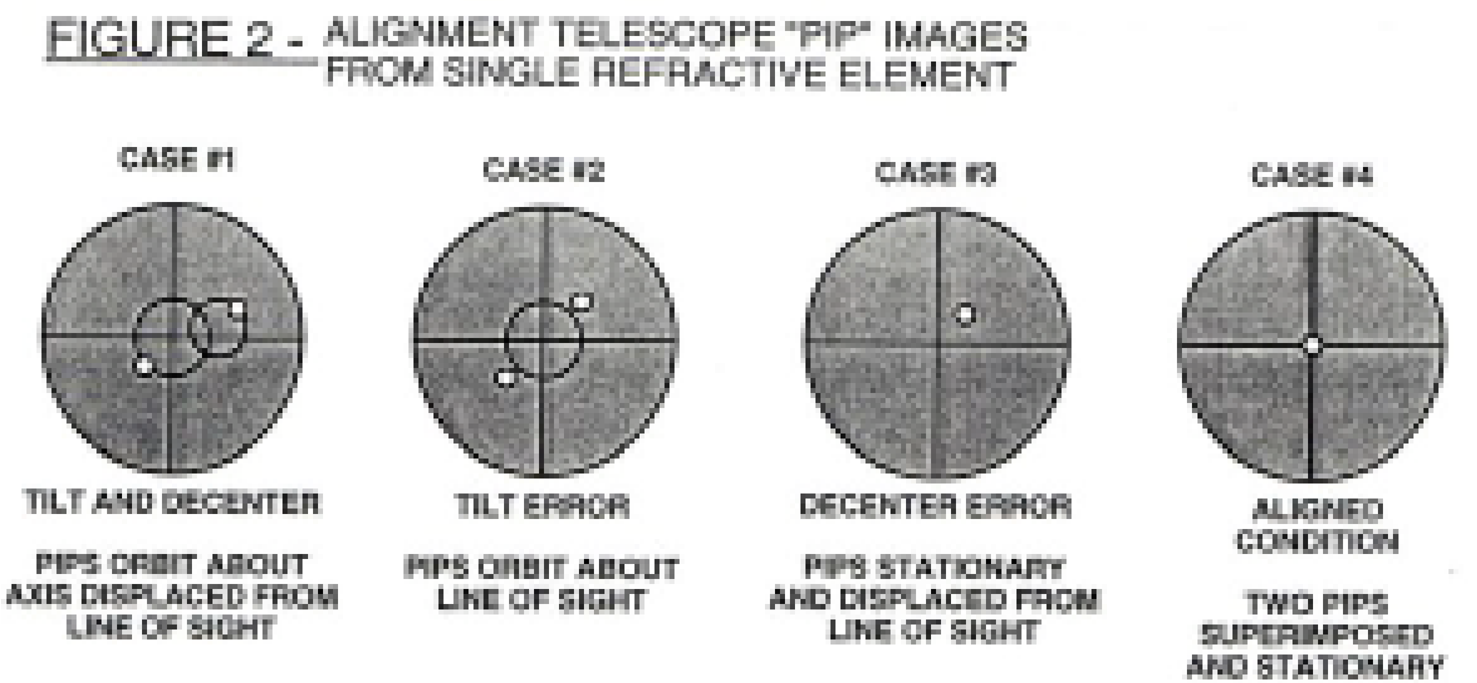
Tools used for alignment – Pip generator

- Accessory for alignment telescope
  - Particularly useful for ones without an internal light source
- Produces a point source of light in front of objective
  - Alignment telescope can focus on real or virtual image of spot
  - Spot usually brighter than internal source on those that have them





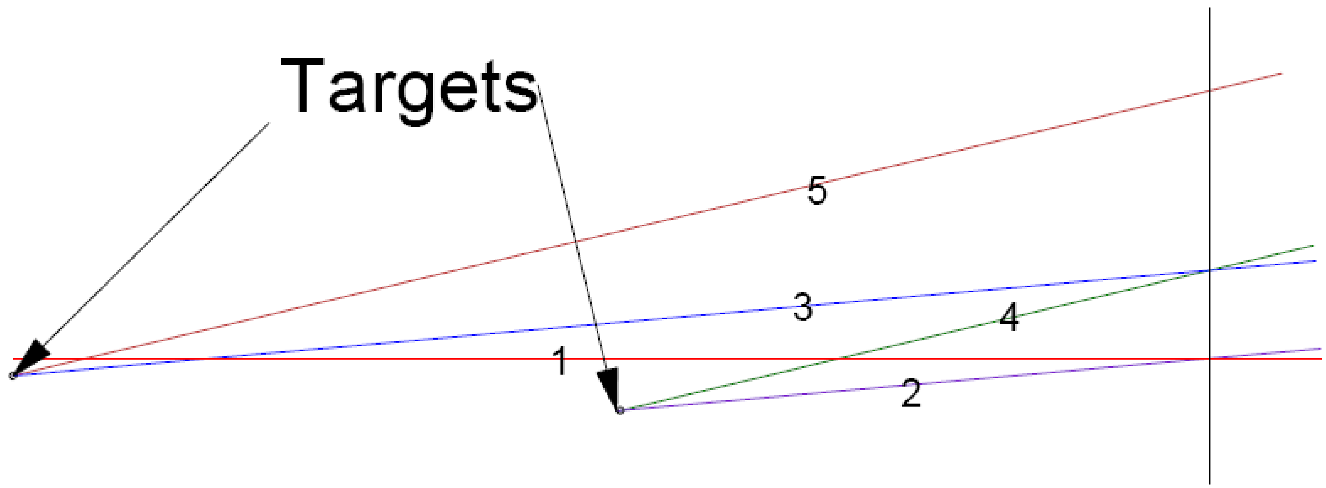
Using an alignment telescope



Return spots shown as though viewed simultaneously, actually at different focus positions

Alignment technique for precision optical assemblies
James J. Kumler and Marc Neer
Proc. SPIE **1996**, 67 (1993).

Aligning to targets – finding an axis

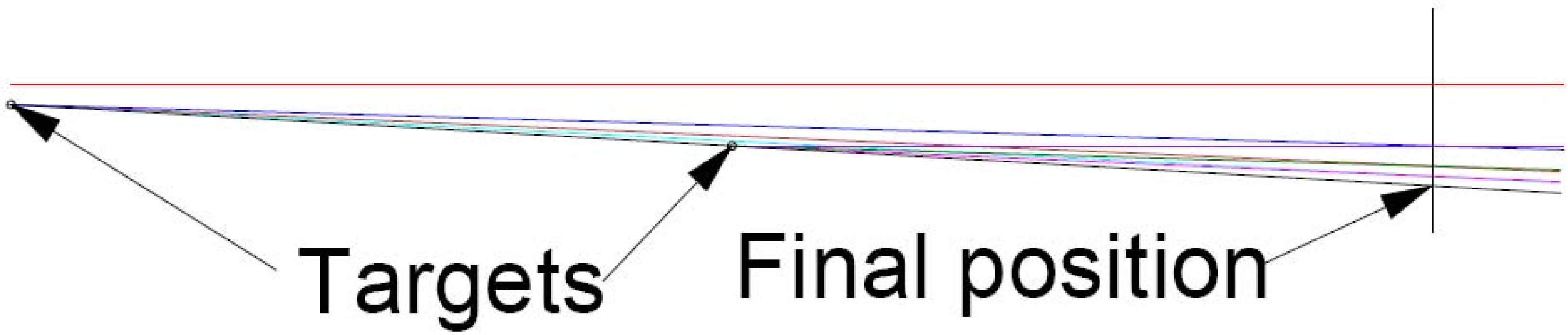


Incorrect procedure: Focus on far target and displace telescope

Focus on near target and rotate

Process does not converge!   Diagram highly exaggerated

Aligning to targets – finding an axis 2

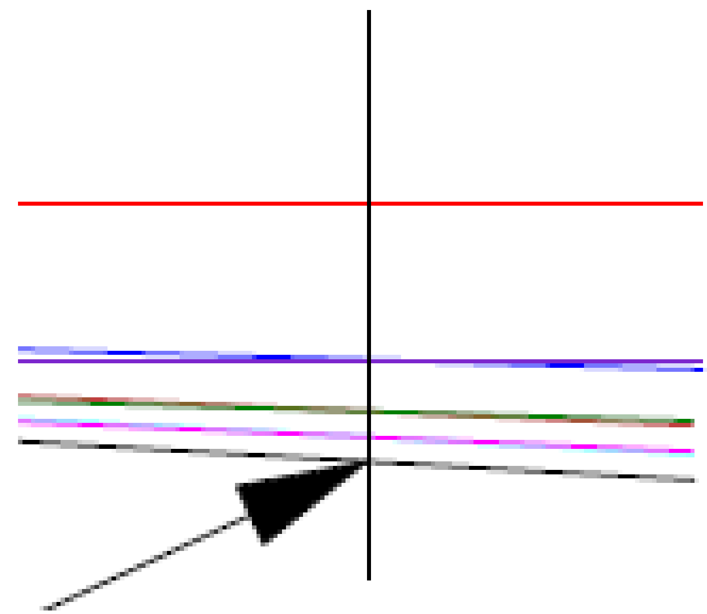


Correct procedure:

Focus on near target and displace

Focus on far target and rotate

Will converge to correct spot

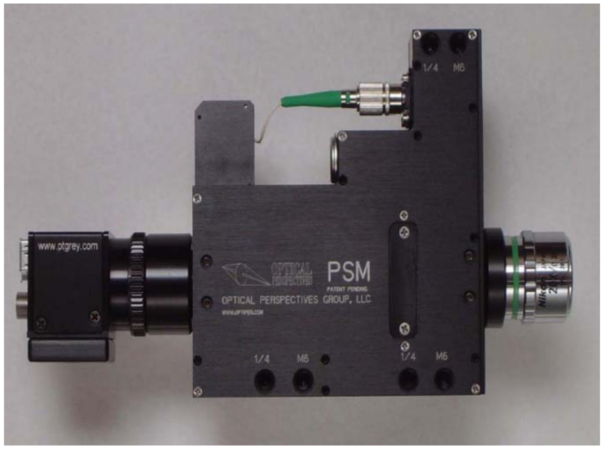


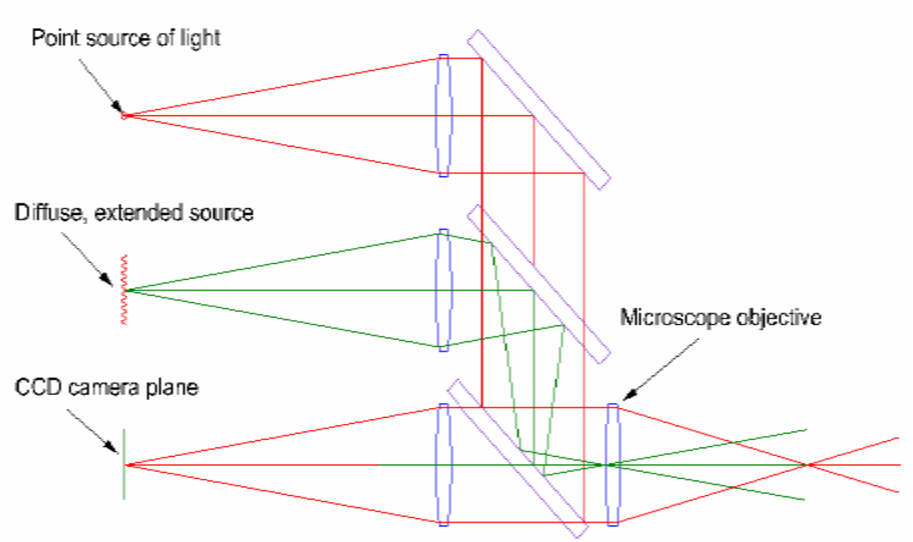
Finding axis like iterating to find a line

	x1	y1	x2	y2	xrot	yrot	m
	-160	19	15	19	185	19	0
displaced	-160	4	15	4		4	0
rotated	-160	14			185	4	-0.02899
	-160	14	15	8.927536			
displaced	-160	14	15	4	185	-0.92754	-0.04327
rotated	-160	14	15	6.428061			
	-160	14	15	4	185	-3.3556	-0.05031
displaced	-160	14	15	5.196436			
rotated	-160	14	15	4	185	-4.55203	-0.05377
	-160	14	15	4.589548			
displaced	-160	14	15	4	185	-5.14158	-0.05548
rotated							
				Final value			0.05747

Tools used for alignment – Autostigmatic microscope

- Forms perfect point image and displays return image
  - Uses internal fiber source and CCD detector
  - Locates return focus in three directions to ~ 1 um
  - Will measure radius of curvature if mounted on optical rail
  - Used for locating centers of curvature and lens conjugates





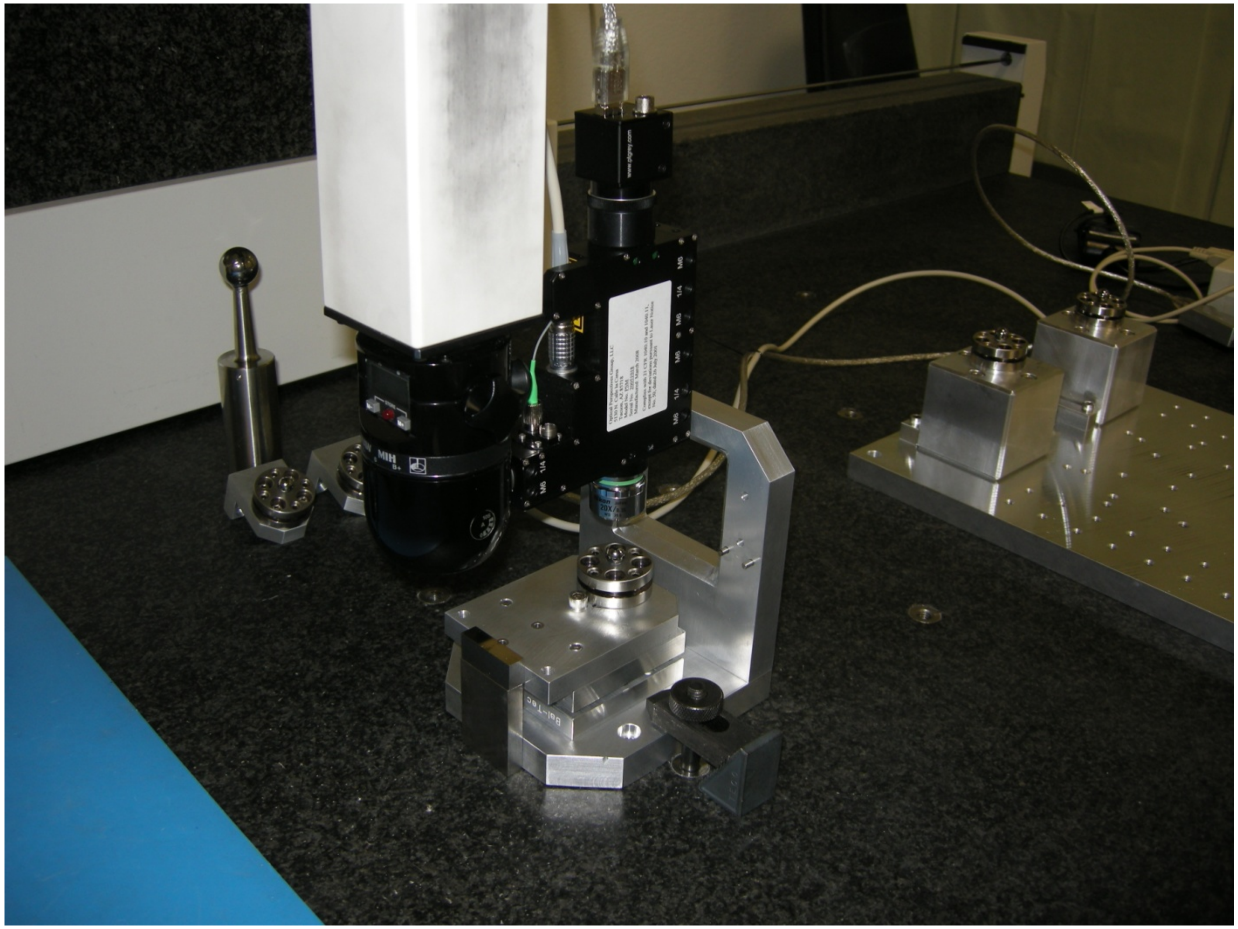
Autostigmatic microscope

Microscope must be positioned mechanically to conjugates or foci
- Can move along rail to establish an axis
- Rail with scale allows axial positioning

Microscope can be moved using a CMM as a large x, y, z stage
- Datums picked up from tooling balls on optical support
- CMM then works in coordinate system of support
- Optics positioned as design shows

Conjugates or foci can be located by means of a fixture
- Post and ball keep optical axis at constant elevation
- Holes in fixture locate posts, post tops serve as ball mounts

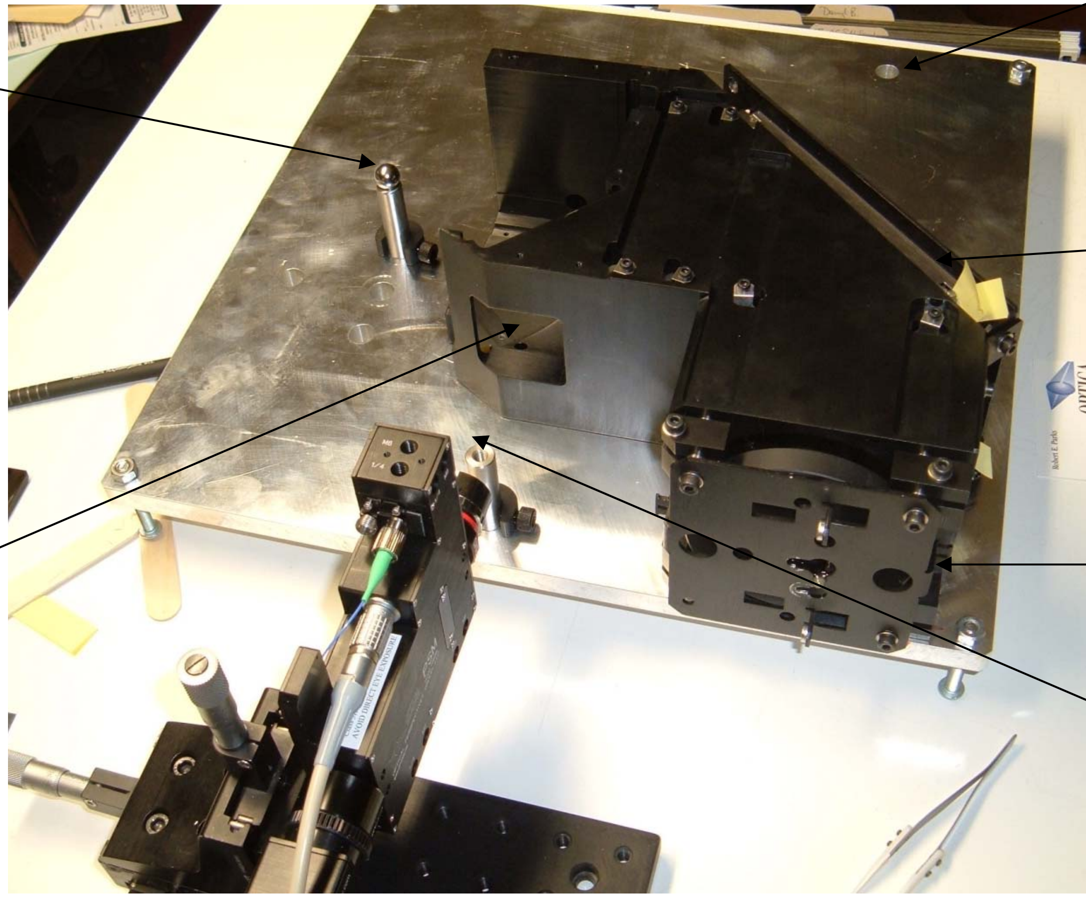
Microscope on a CMM



Alignment of 3-D systems
Spectrometers and Offner relays

Output focus & return sphere to autocollimate system

Input fold mirror



Fixture with post holes to define conjugates

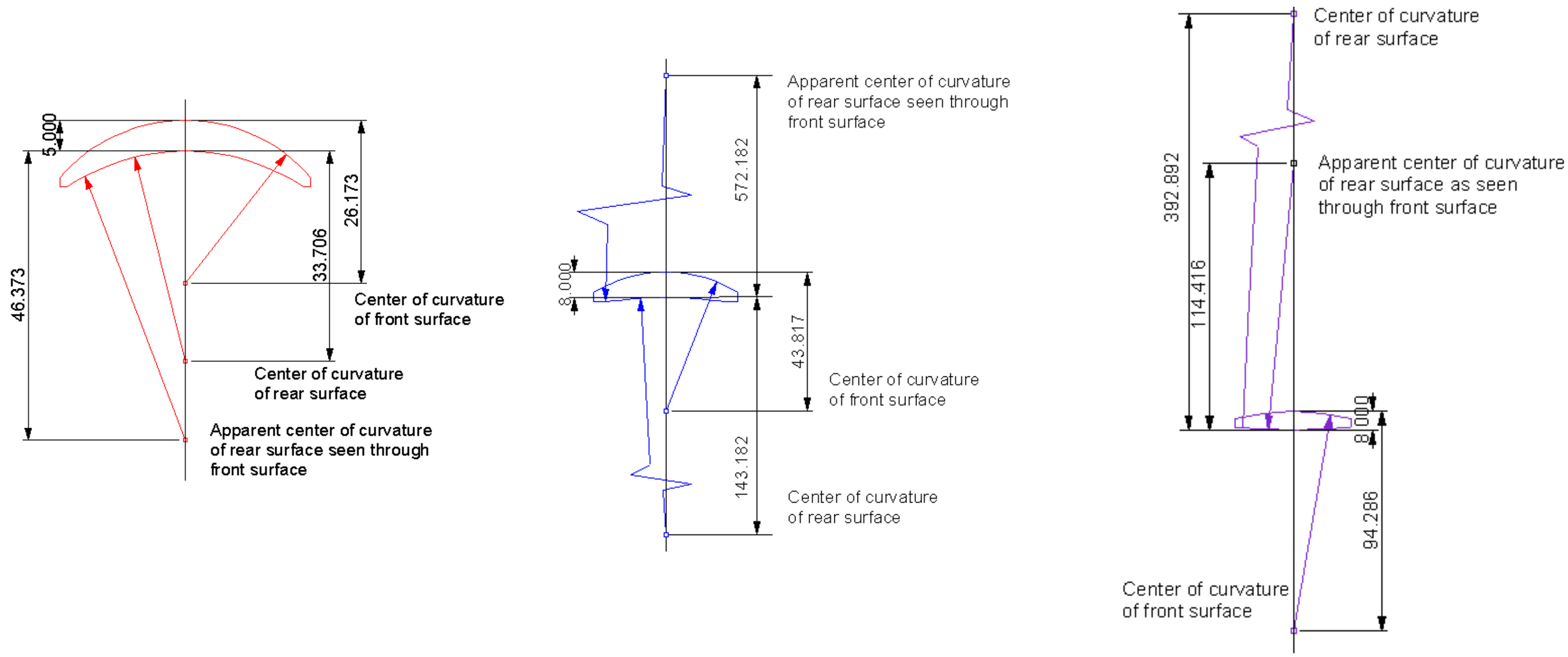
Fold mirror

Offner mirror

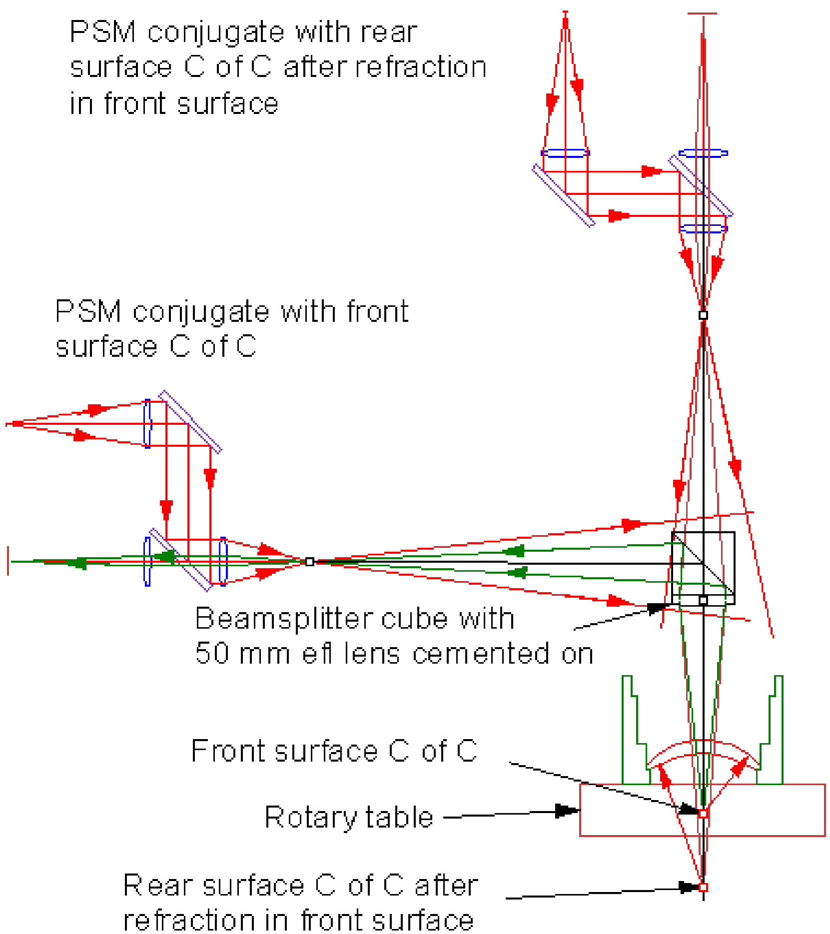
Input focus

OPTICAL PERSPECTIVES

Location of C's of C



View both C's of C simultaneously

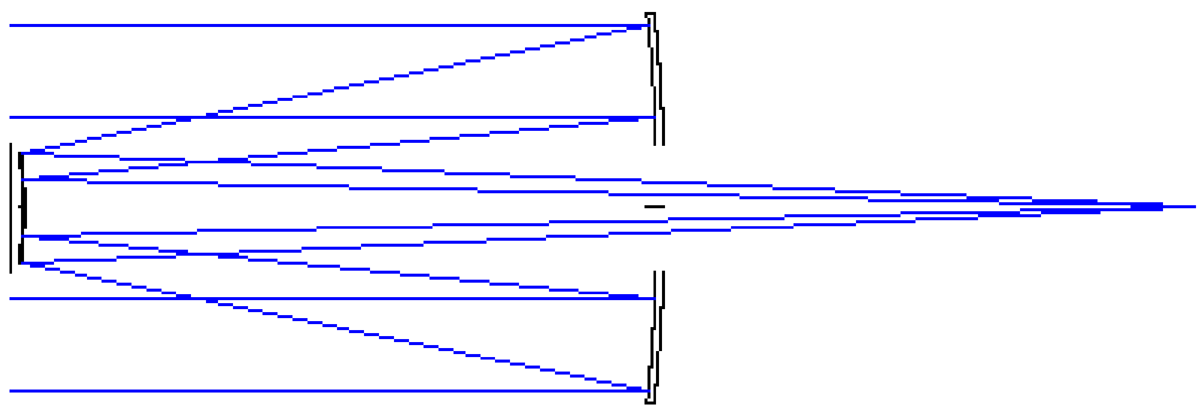


Zemax Ritchey-Chretien

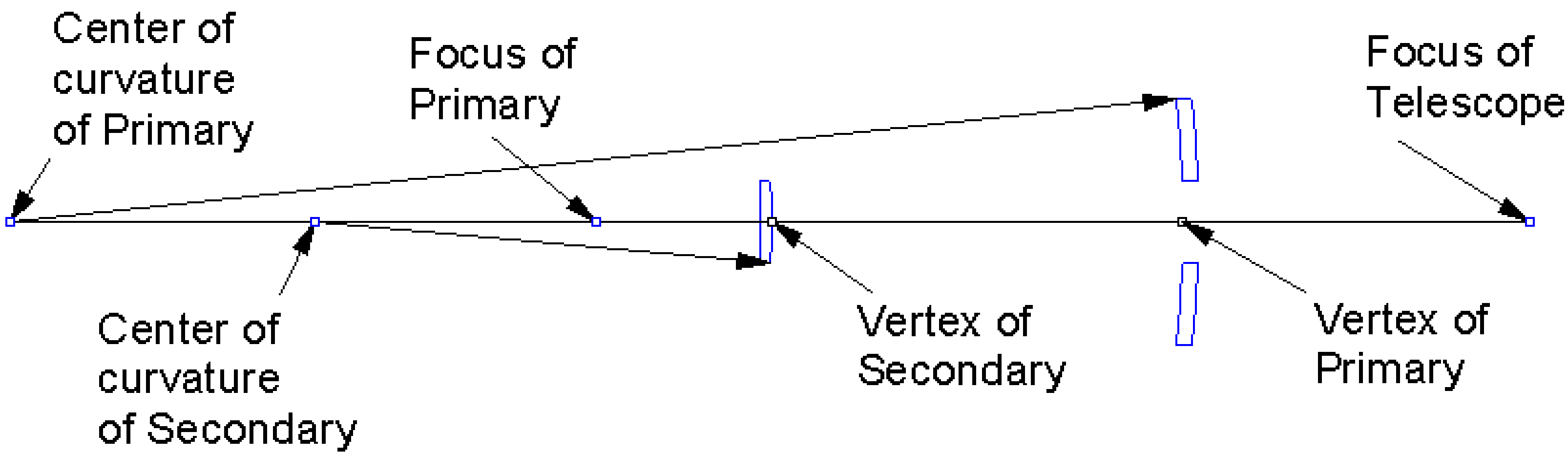
Lens Data Editor

Edit Solves View Help

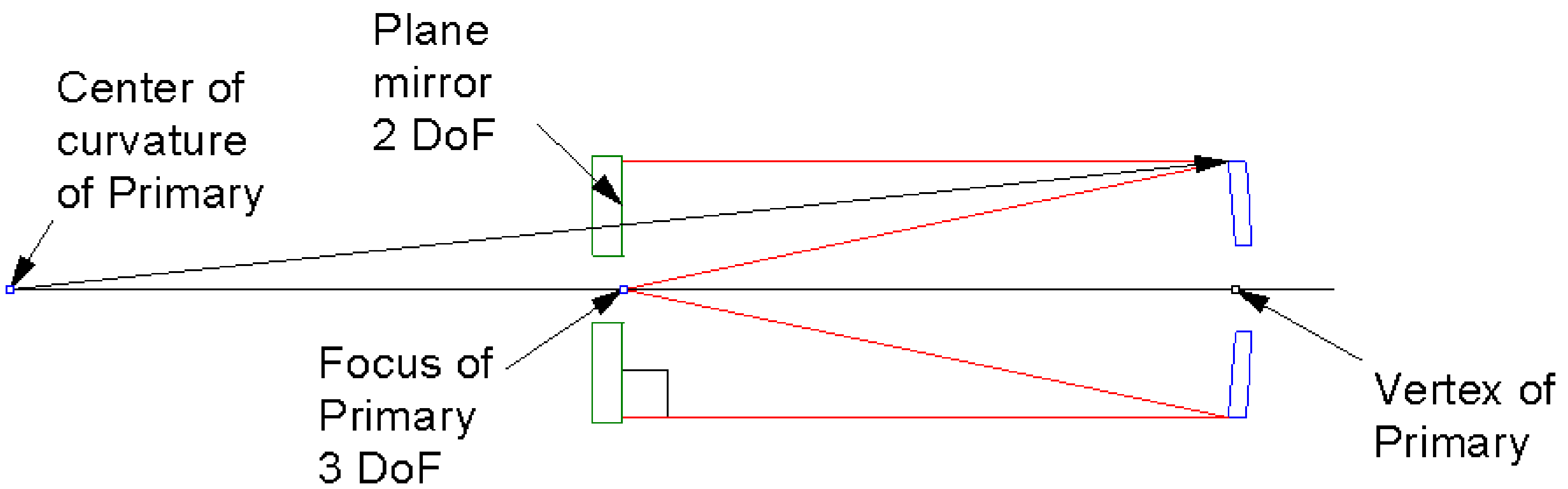
Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic	
OBJ	Standard		Infinity		Infinity				0.000000		0.000000	
1*	Standard		Infinity		265.00000				26.000000	U	0.000000	
STO*	Standard	Primary	-742.857201		-260.0000		MIRROR		78.000000	U	-1.04619	
3	Standard	Secondary	-290.232796		479.99955	V	MIRROR		22.565773		-2.91500	
IMA	Standard		Infinity		-				1.39853E-005		0.000000	



Conjugates of R-C telescope



Finding axis of Primary

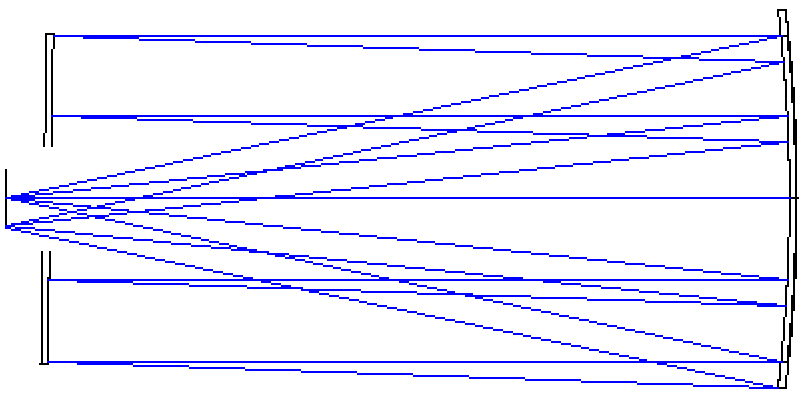


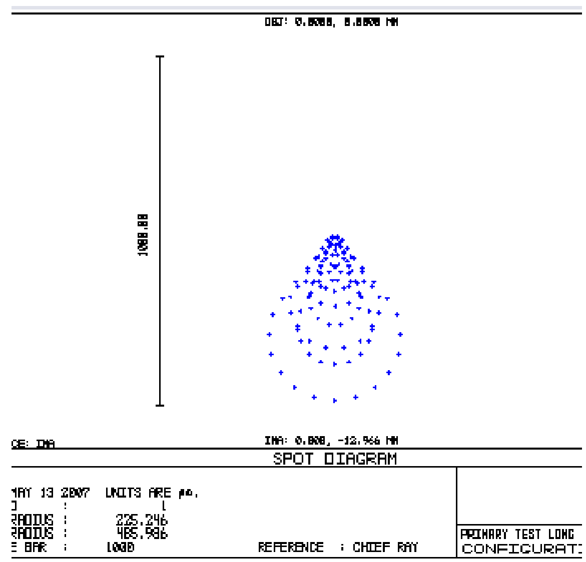
How test works

- If rays parallel to OA, image is coma free – Defines 2 DoF
- If object & image points coincident, plane mirror is perpendicular to rays, 3 DoF
- If both hold, focus is on OA and so are CofC and Primary vertex

Zemax model – initial case

Comment	Radius		Thickness		Glass	Semi-Diameter	Conic		Pa..	De..	De..	Tilt About X	
	Infinity		371.49078			0.000000	0.000000						
Primary	-742.8570		-350.0000		MIRROR	77.158745	-1.04619						
			0.000000		-	0.000000				*	*	1.000000	
Flat	Infinity		0.000000		MIRROR	77.176344	0.000000						
			350.00000		-	0.000000				*	*	-1.000000	P
Primary 2nd pass	-742.8570	P	-371.4908	P	MIRROR	89.252518	-1.04619	P					
	Infinity		-			13.452388	0.000000						

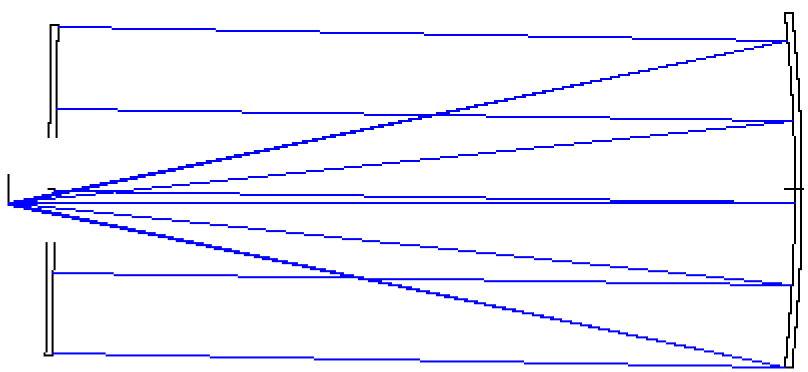


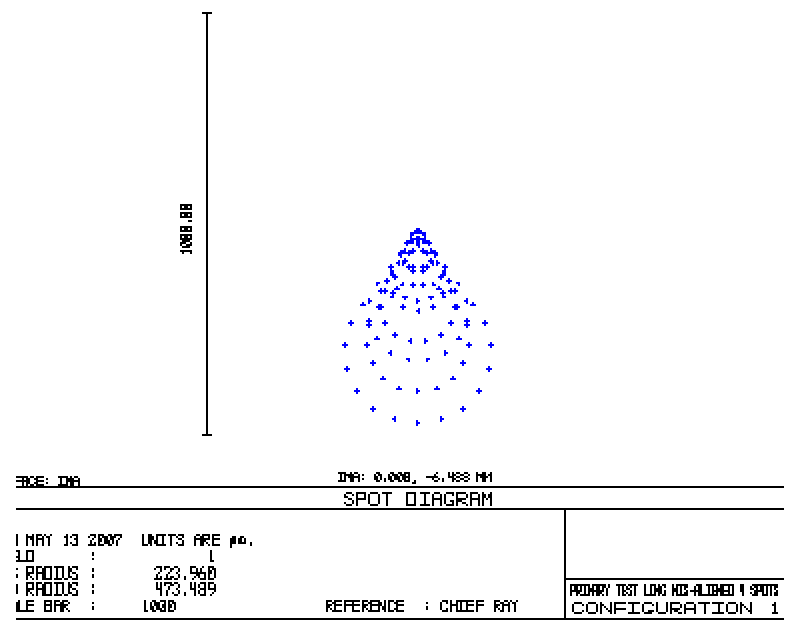


Zemax model – O & I coincident

Solves View Help

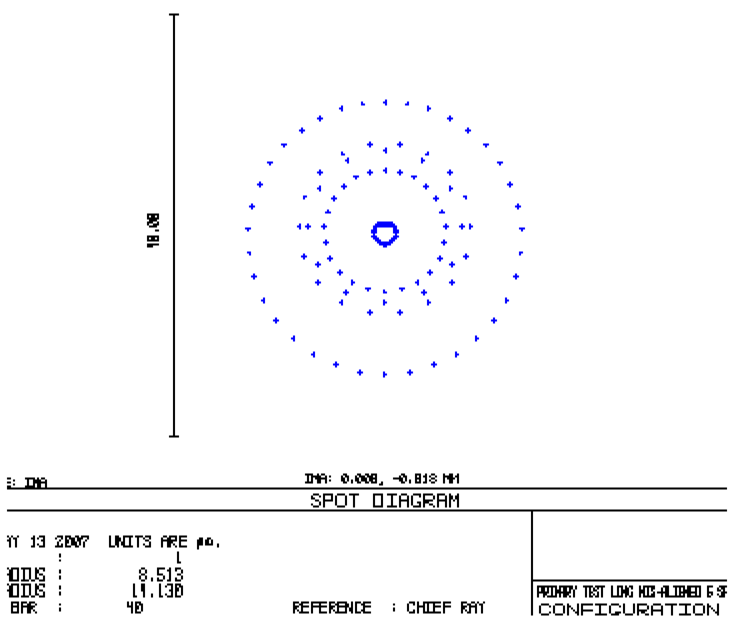
Surf:Type	Comment	Radius		Thickness		Glass		Se..		Conic		Par..		De..		Decenter Y		Tilt About X	
Standard		Infinity		0.000000				*		0.00000									
Coordinate B..				371.490782		-		*						*		6.482826	V	0.000000	
Standard	Primary	-742.8570		-350.000000		MIRROR		*		-1.0462									
Coordinate B..				0.000000		-		*						*		0.000000		1.000000	
Standard	Flat	Infinity		0.000000		MIRROR		*		0.00000									
Coordinate B..				350.000000	P	-		*						*		0.000000		-1.000000	P
Standard	Primary 2nd pass	-742.8570	P	-371.490782	P	MIRROR		*		-1.0462	P								
Standard		Infinity		-				*		0.00000									

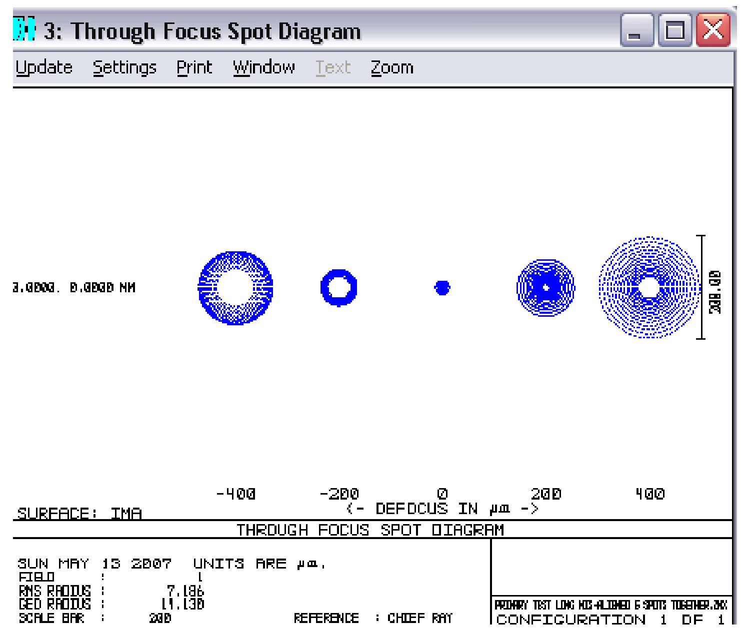




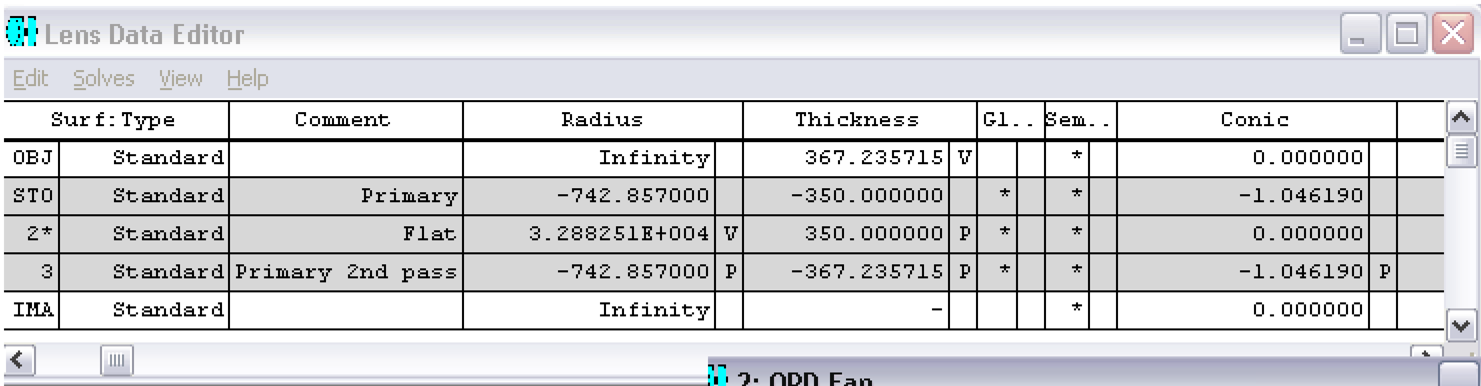
Zemax model – 10 seconds tilt

Surf	Type	Conic	Par 0..	Par 1 (unused)	Par 2 (unused)	Par 3 (unused)
OBJ	Standard	0.000000				
1	Coordina..			0.000000	0.018022 V	0.000000
STO	Standard	-1.046190				
3	Coordina..			0.000000	0.000000	2.780000E-003
4*	Standard	0.000000				
5	Coordina..			0.000000	0.000000	-2.780000E-003 P
6	Standard	-1.046190 P				
IMA	Standard	0.000000				





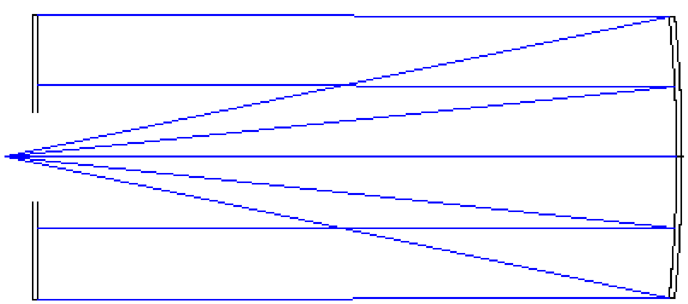
Primary test compensated

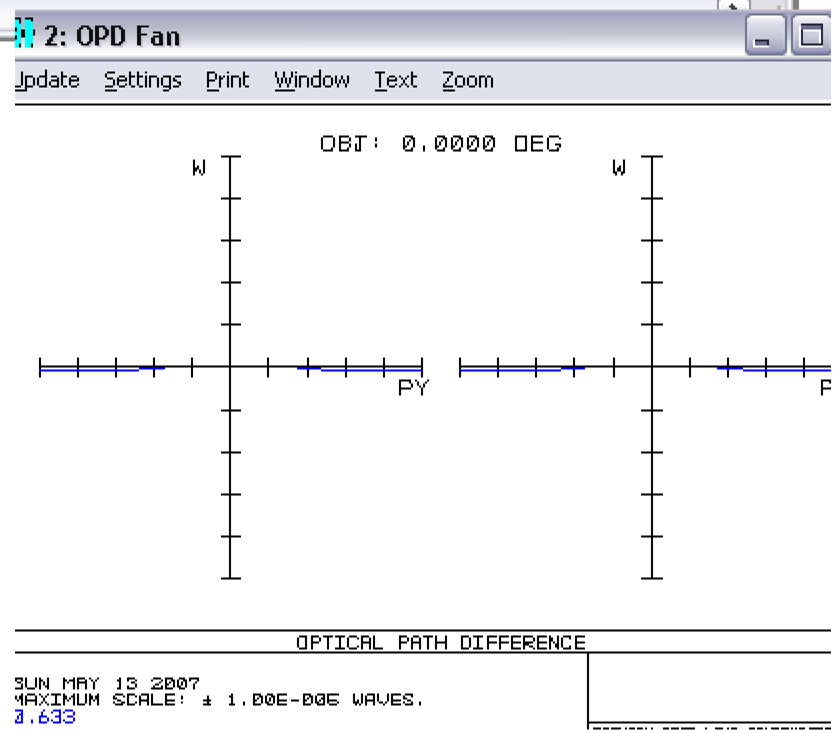


Lens Data Editor

Edit Solves View Help

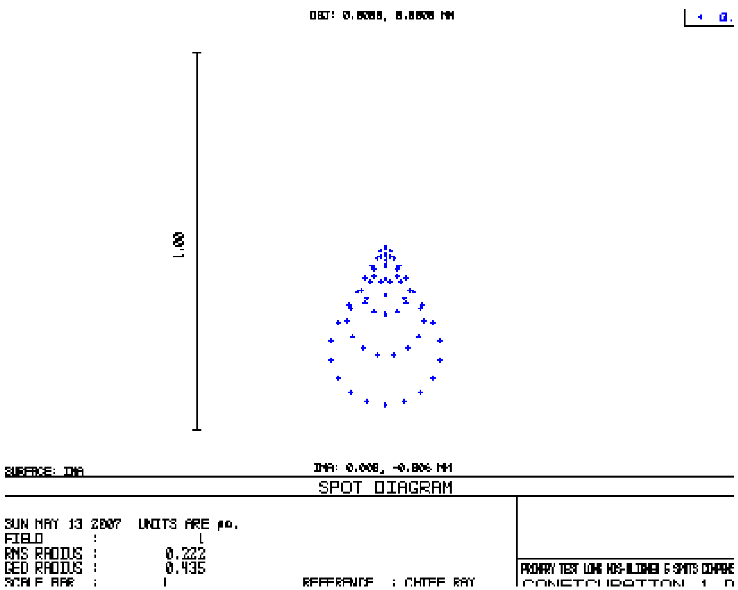
Surf:Type		Comment	Radius		Thickness		Gl..	Sem..	Conic	
OBJ	Standard		Infinity		367.235715	V		*	0.000000	
STO	Standard	Primary	-742.857000		-350.000000		*	*	-1.046190	
2*	Standard	Flat	3.288251E+004	V	350.000000	P	*	*	0.000000	
3	Standard	Primary 2nd pass	-742.857000	P	-367.235715	P	*	*	-1.046190	P
IMA	Standard		Infinity		-			*	0.000000	

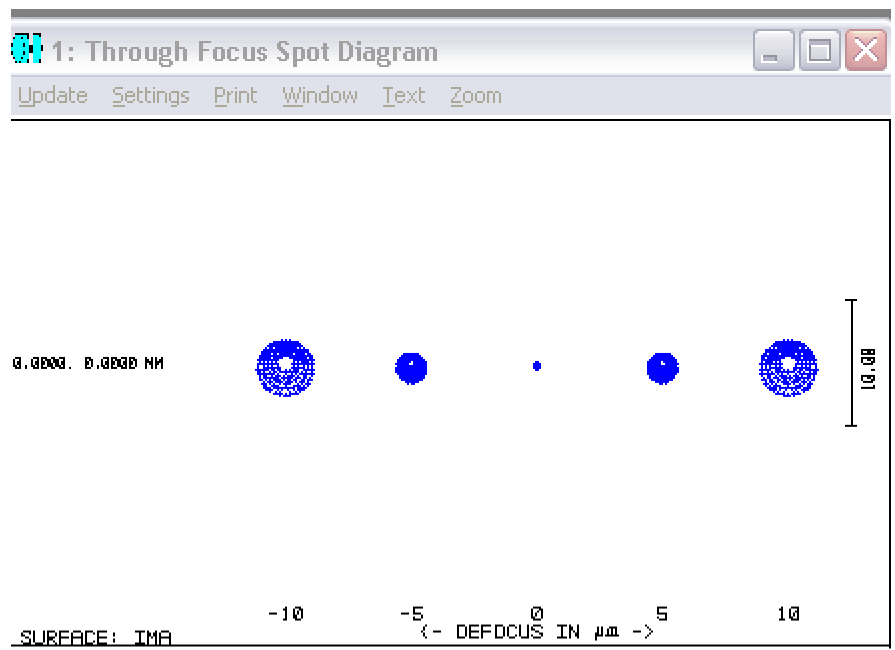




Compensated test – 3-4 seconds tilt

	Surf:Type	Radius		Thickness		G..	S..	Conic		P..	Pa..	Par 2(unused)		Par 3(unused)	
BJ	Standard	Infinity		0.000000				0.000000							
1	Coordinate B..			367.235650		-					*	6.478428E-003	V	0.000000	
TO	Standard	-742.857000		-350.000000		*		-1.046190							
3	Coordinate B..			0.000000		-					*	0.000000		1.000000E-003	
4*	Standard	3.288200E+004		0.000000		*		0.000000							
5	Coordinate B..			350.000000	P	-					*	0.000000		-1.000000E-003	P
6	Standard	-742.857000	P	-367.235650	P	*		-1.046190	P						
MA	Standard	Infinity		-				0.000000							

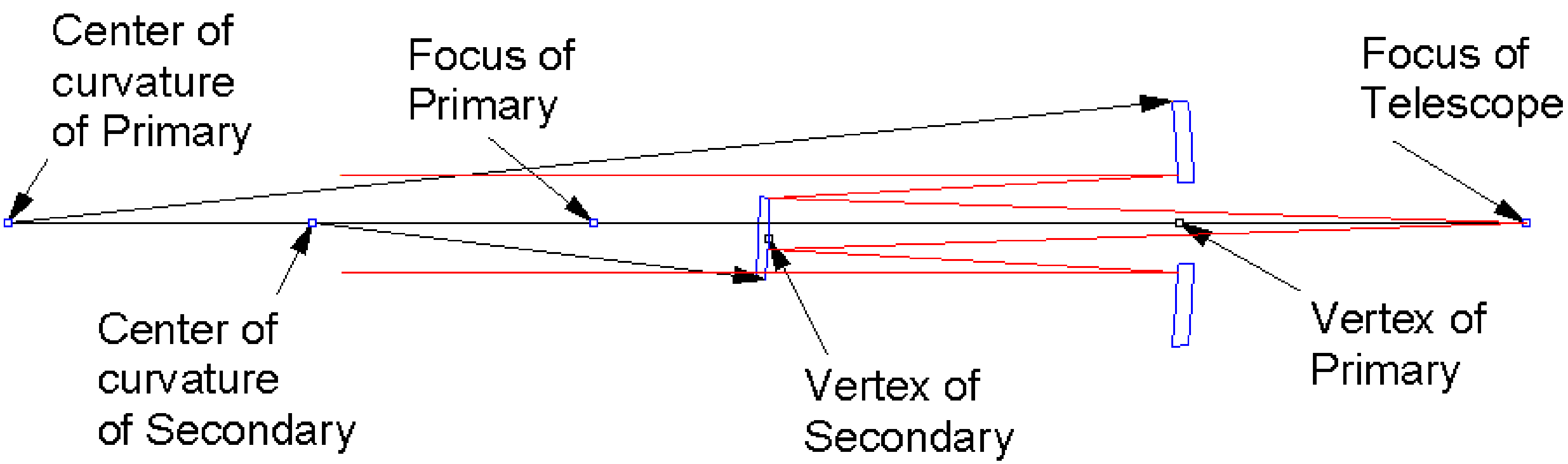




Secondary alignment

- Collimating mirror is square with primary
- Two ways to align secondary
  - Locate object on OA, tilt sec for coincidence
    - Image coincidence means C of C on optical axis
    - Image just has coma
    - Quickest, easiest but requires tooling
  - Use aberrations and go through focus
    - Image will have both coma and astigmatism
    - Better for one off, no tooling required

Secondary alignment – object on axis



To first order a ray from focus to C of C of secondary will strike secondary at normal incidence

Secondary alignment – DoF

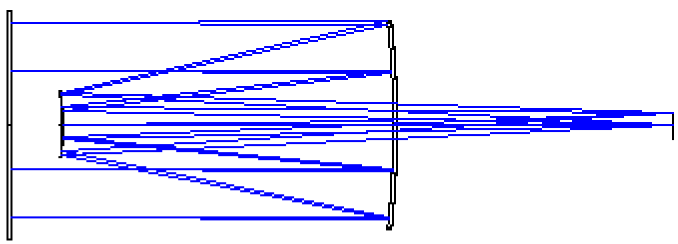
- Secondary aligned in 5 DoF
  - 3 translation; 2 decenter, 1 focus
  - 2 tilt
- Must constrain DoF in manufacturing of components (possible in aluminum with diamond turning) or by with adjustments (motions) in secondary mount
- With good mechanisms - alignment is a matter of minutes

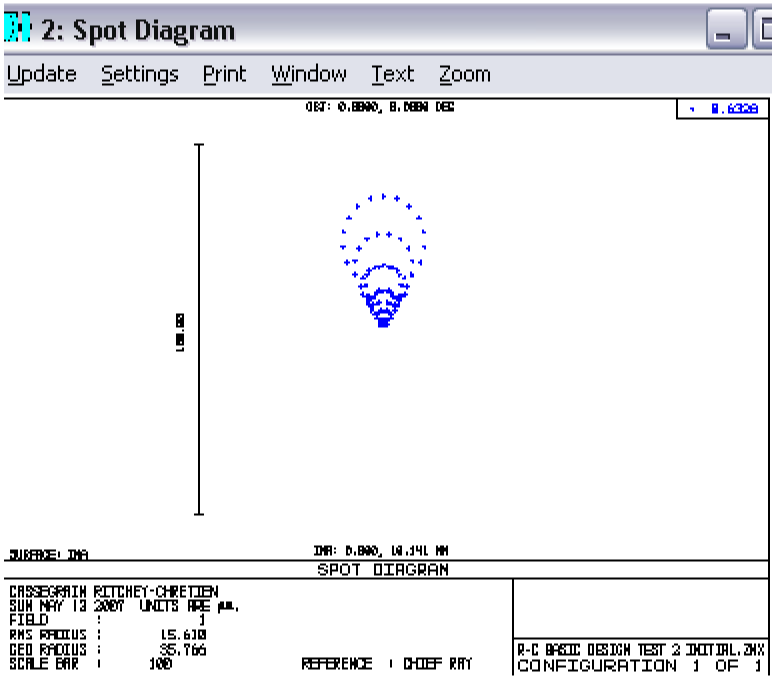
Secondary alignment – initial state

Secondary +1.0 mm y dec, +0.5º x tilt

so secondary vertex 1 mm above axis, and C of C 1.533 mm below axis

Image is 10.141 mm above axis

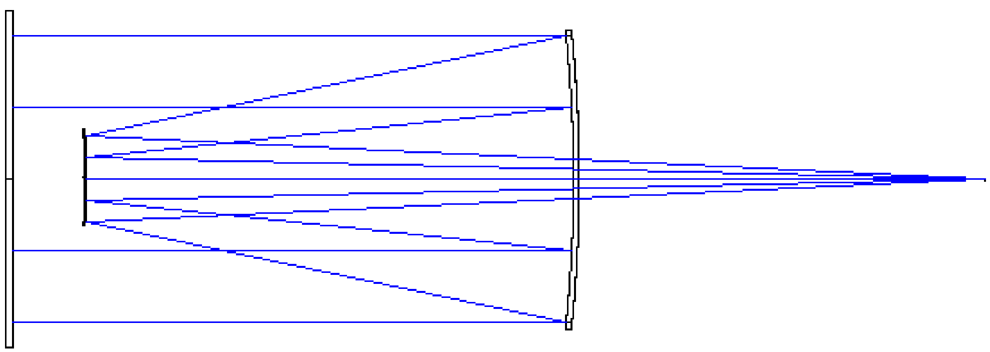


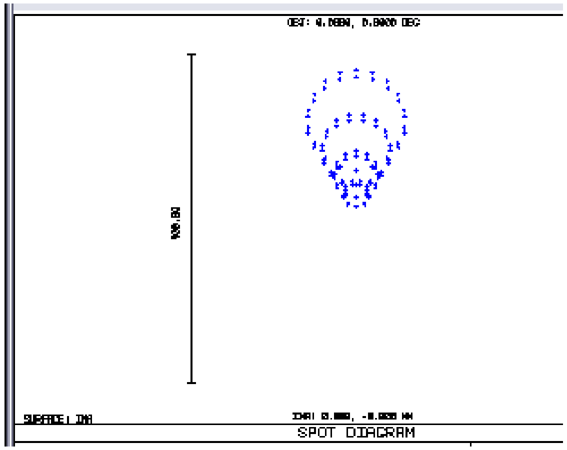


Secondary alignment – O & I coincident

Secondary tilt reduced by .3026º to .1974º, C of C on optical axis

Telescope image is also on axis, almost pure coma, about half a wave





Finish alignment by a combination of tilt and decenter of secondary that keeps image on axis while coma is reduced.

Easily improved to tenth wave level. Notice no spherical aberration.

Secondary alignment – no tooling

Secondary -0.9 mm y dec, -0.5º x tilt
so secondary vertex 0.9 mm below axis, and C of C 1.633 mm below axis
Image is 5.4 mm above axis, a fifth the radius of the primary hole

Even though image is small, it is mostly astigmatic; C of C not on axis