Straightforward solutions to a challenging problem

We're going to talk about how to align off-axis optics – usually sections of rotationally symmetric surfaces such as mirrors, but could be lens sections, too.

We'll discuss the optical and mechanical aspects of my favorite and most general alignment technique – a real workhorse method– and in doing so learn a great deal about the nature of these surfaces.

We'll also discuss two methods for aligning off-axis parabolas -- a very common type of off-axis aspheric. More about this later.

The Grouping of Off-axis Systems by Alignment Classification

- Experience has shown that the alignment of off-axis systems can often be grouped based on the answers to three questions:
  1. Was the off-axis piece cut from a rotationally symmetric parent or was it manufactured as a stand-alone piece?
  2. Will the parent optical axis be accessible or not during alignment?
  3. Is the aspheric a parabola ($k = -1$) or is the surface another conic ($k \neq -1$) or general, higher order asphere?
- Different combinations of answers to these three questions impacts the alignment techniques used and is a good alignment plan starting point

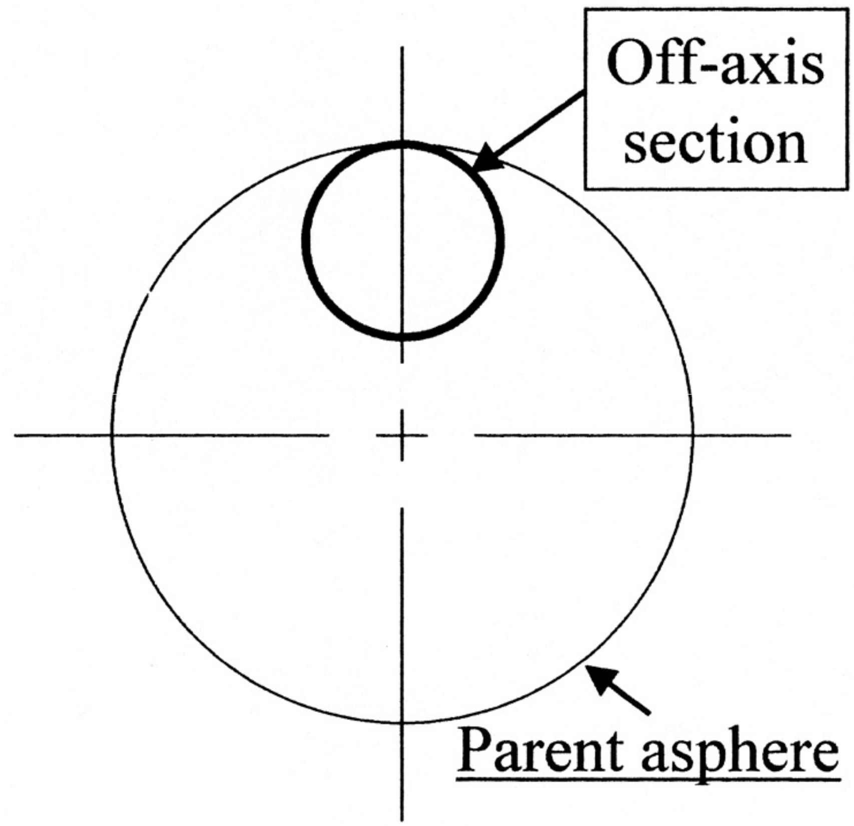
Off-axis alignment examples

- We will examine three interesting cases:
  - A general, higher order aspheric surface, cut from a parent asphere, having its optical axis accessible*
  - A parabola, fabricated as a stand-alone optic, having its optical axis accessible
  - A parabola, fabricated as a stand-alone optic, not having its optical axis accessible

***This is a very useful technique.**

What is an Off-axis Aspheric Mirror?

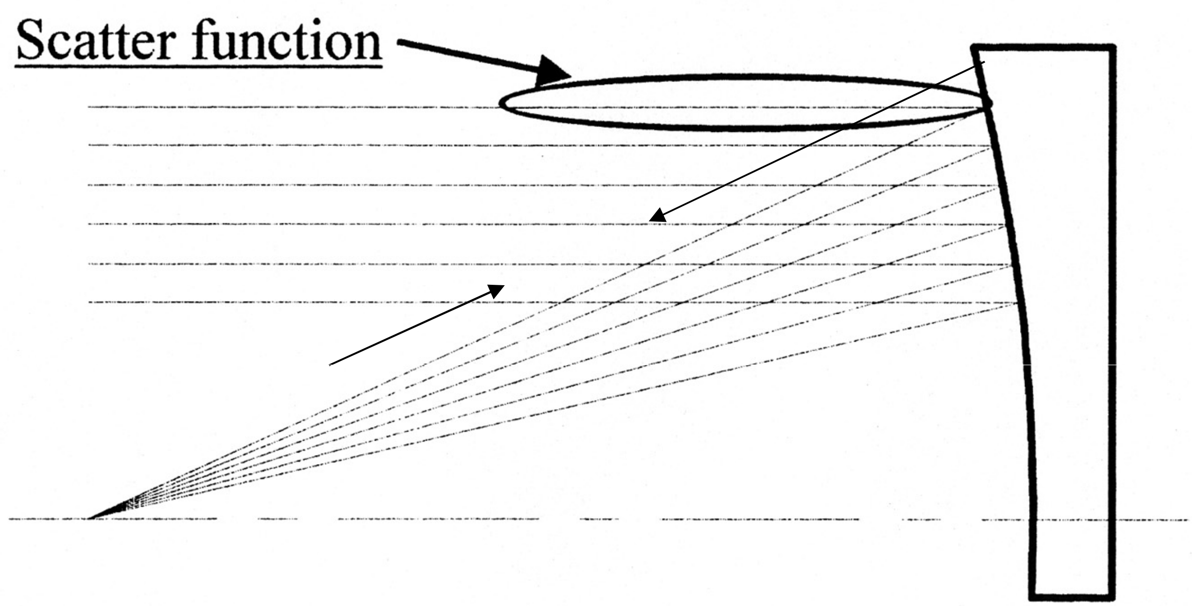
- Section of a rotationally symmetric parent mirror
- Could contain optical axis
- Remember: No such thing as an off-axis sphere!



When & why are off-axis optics used?

- In general, when the obscurations in reflecting systems cannot be tolerated:
  - High energy laser systems
  - Transmit/receive systems
  - Low glare/stray light requirements
  - Looking at faint stuff near a bright object
  - Require good MTF at mid-spatial frequencies
  - Require good Airy disk
- Segmented optics (e.g. NGST)

Off-axis Optics Have Low Backscatter

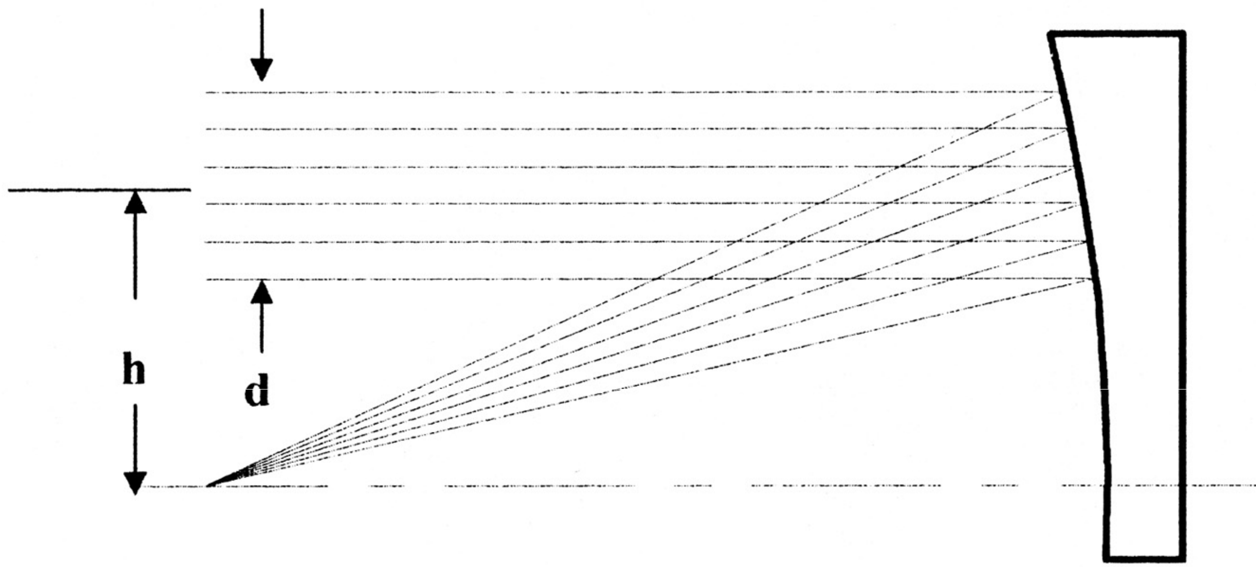


- In transmit/receive systems the return backscatter is reduced as the optic is further off-axis.

Aligning Off-Axis Aspheric Mirrors

- Why are they so difficult to align?
  - Non-rotationally symmetric surfaces which adds a degree of freedom for misalignment
  - The optical axis is not parallel to the gut ray
  - Adjustments are highly non-orthogonal and iterate poorly to a solution

Off-axis Asphere--Parameters

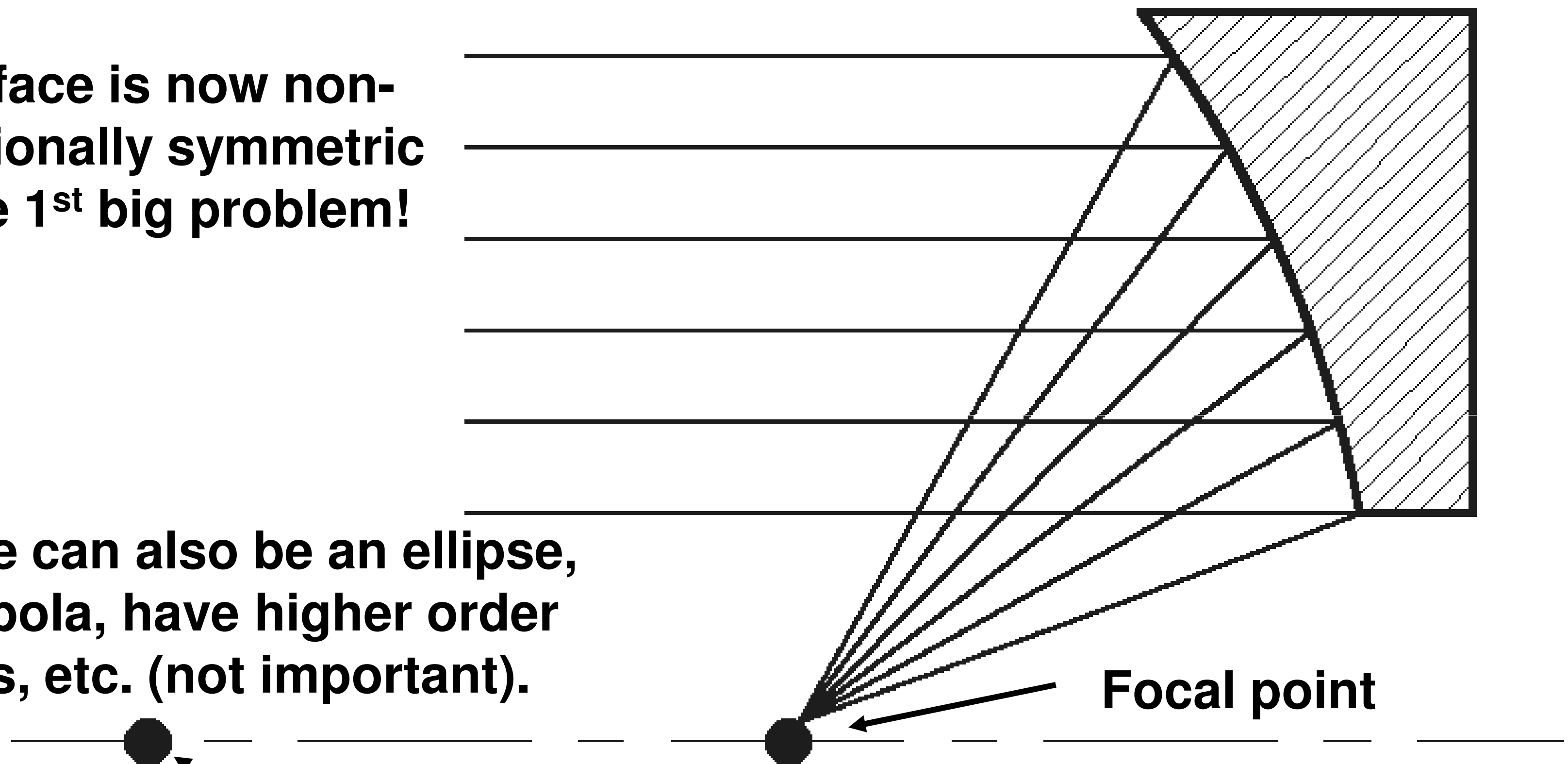


- Paraxial base radius, R; conic constant, κ; higher order aspheric coefficients A, B, C,…
- Clear aperture diameter, d
- Displacement of aperture from parent axis, h

Example: Off-axis parabola

Surface is now non-rotationally symmetric – the 1st big problem!

Surface can also be an ellipse, hyperbola, have higher order terms, etc. (not important).



Spheres, Parabolas & Spherical Aberration

- If we're going to use spherical aberration to help align off-axis aspherics, we need to review when it is and isn't present...
- Spheres & parabolas may or may not have spherical aberration, depending on the conjugates. People get confused.
- The following chart will hopefully clarify this point, quickly.

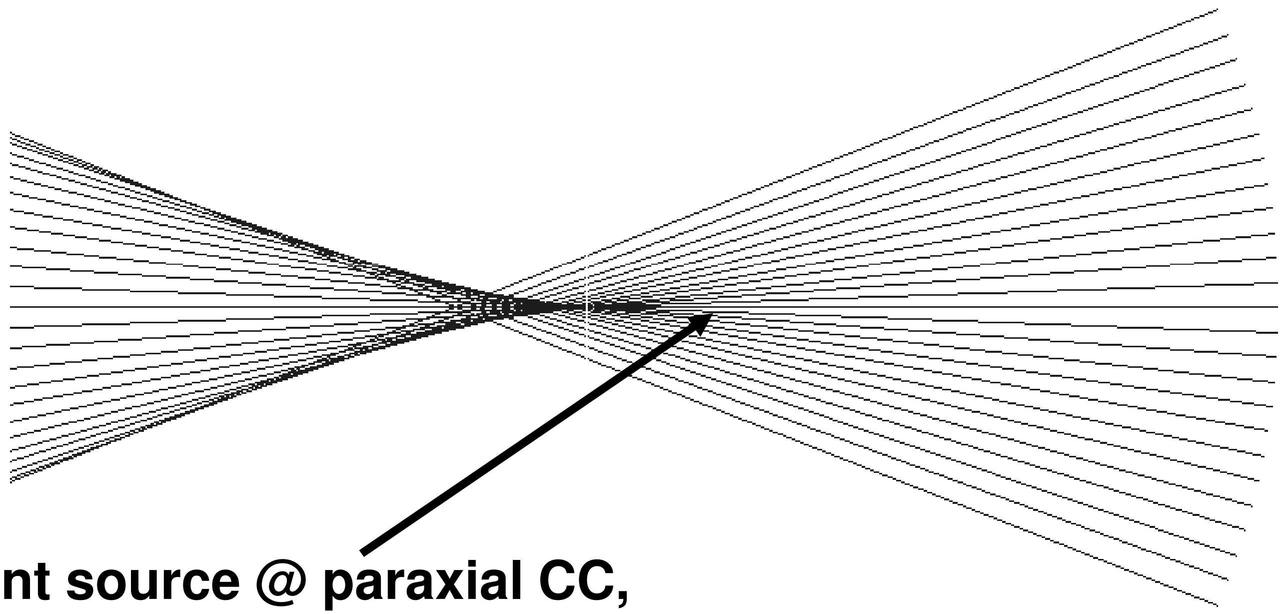
Spheres & parabolas: When SA3 is present & when it isn't

- **For a sphere:**
  - **A point source at the CC gets imaged back on itself (i.e. at the CC) aberration free.**
  - **A point source at ∞ gets imaged at the *focal point* (1/2 the radius of curvature) with (-) SA3**
- **For a parabola:**
  - **A point source at CC gets imaged back on itself with (+) SA3.**
  - **A point source at ∞ gets imaged at the *focal point* (1/2 the radius of curvature) aberration free.**

Any asphere with point source@ CC exhibits SA3!!

This is significant because it means that the "workhorse" alignment technique soon to be discussed is capable of aligning *any* asphere, regardless of the coefficients!

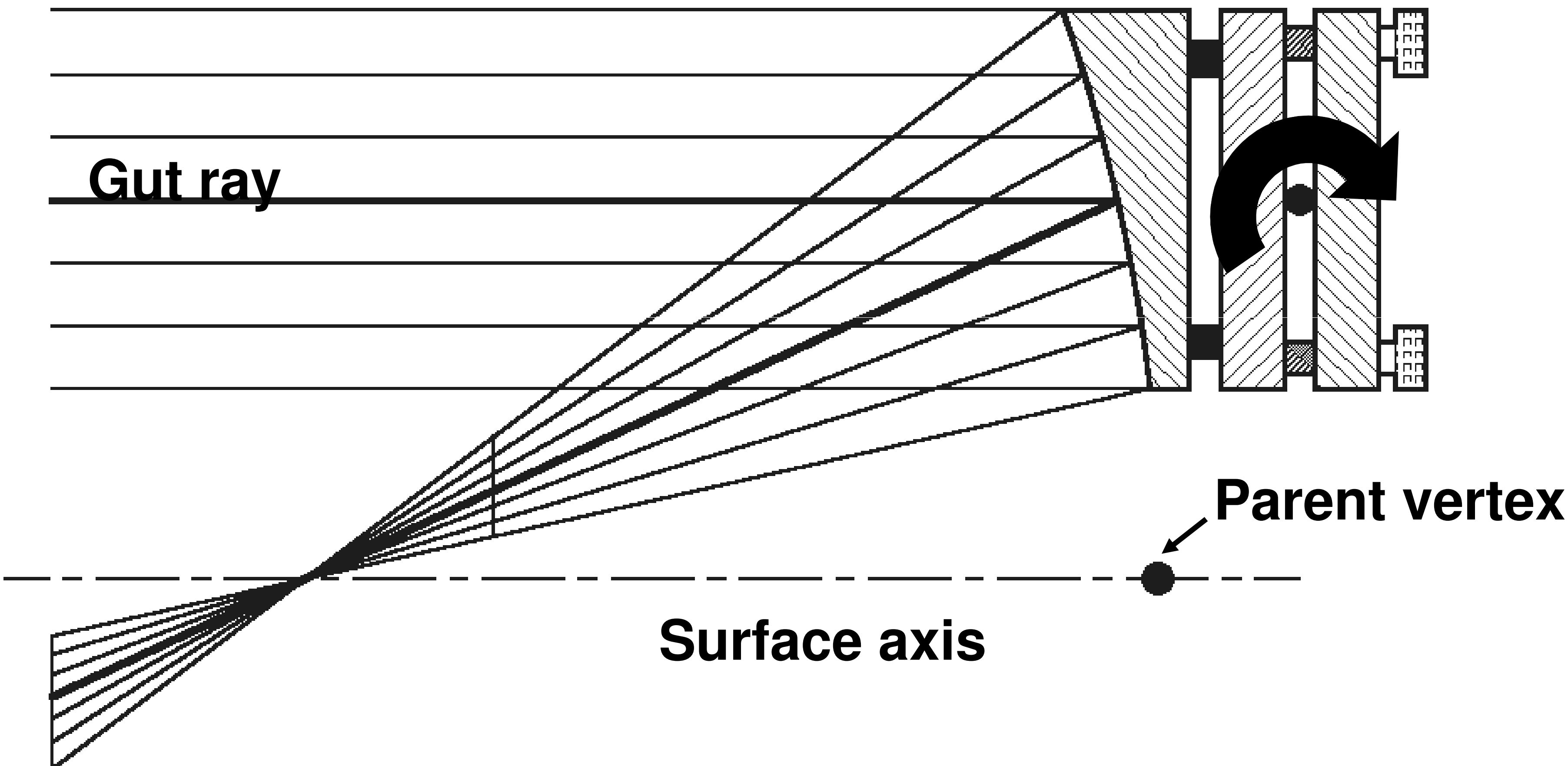
A parabola, point source @ CC



Point source @ paraxial CC,
(outbound rays not shown
for clarity)

What's the other problem?

A conventional mount severely couples tilt, decenter and defocus



Which axis is the correct one? It depends…

Cross-coupling of adjustments

- Focus shift changes image position
- Tip/tilt changes image position
- Tip/tilt changes focus $\therefore$ changes position
- Tip/tilt changes decenter $\therefore$ Δ position

Result: Severe cross-coupling of adjustments that causes confusion, frustration and poorly aligned optics!

A good alignment procedure needs to…

- Solve the non-rotational symmetry issue of the off-axis piece
- Design a mount that makes sense
- And, most importantly, interpret, correctly, the aspects of the return image at the CC of the OAA – it has a weird shape – and understanding spherical aberration is the key to doing so.

First example:

- The surface is cut from a rotationally symmetric parent aspheric surface
- The optical axis will be accessible during the alignment procedure
- The surface is a general aspheric with higher order coefficients

Our approach

- First we discuss spherical aberration in some detail because that is crucial in the understanding of how to do this.
- Second we discuss how to find the vertex of a parent aspheric when only the off-axis piece is present – one of the two points we need.
- Next we learn how to find the center of curvature of the surface – the other point we need.
- Finally we put it all together and we're done!

The Approach in a Nutshell

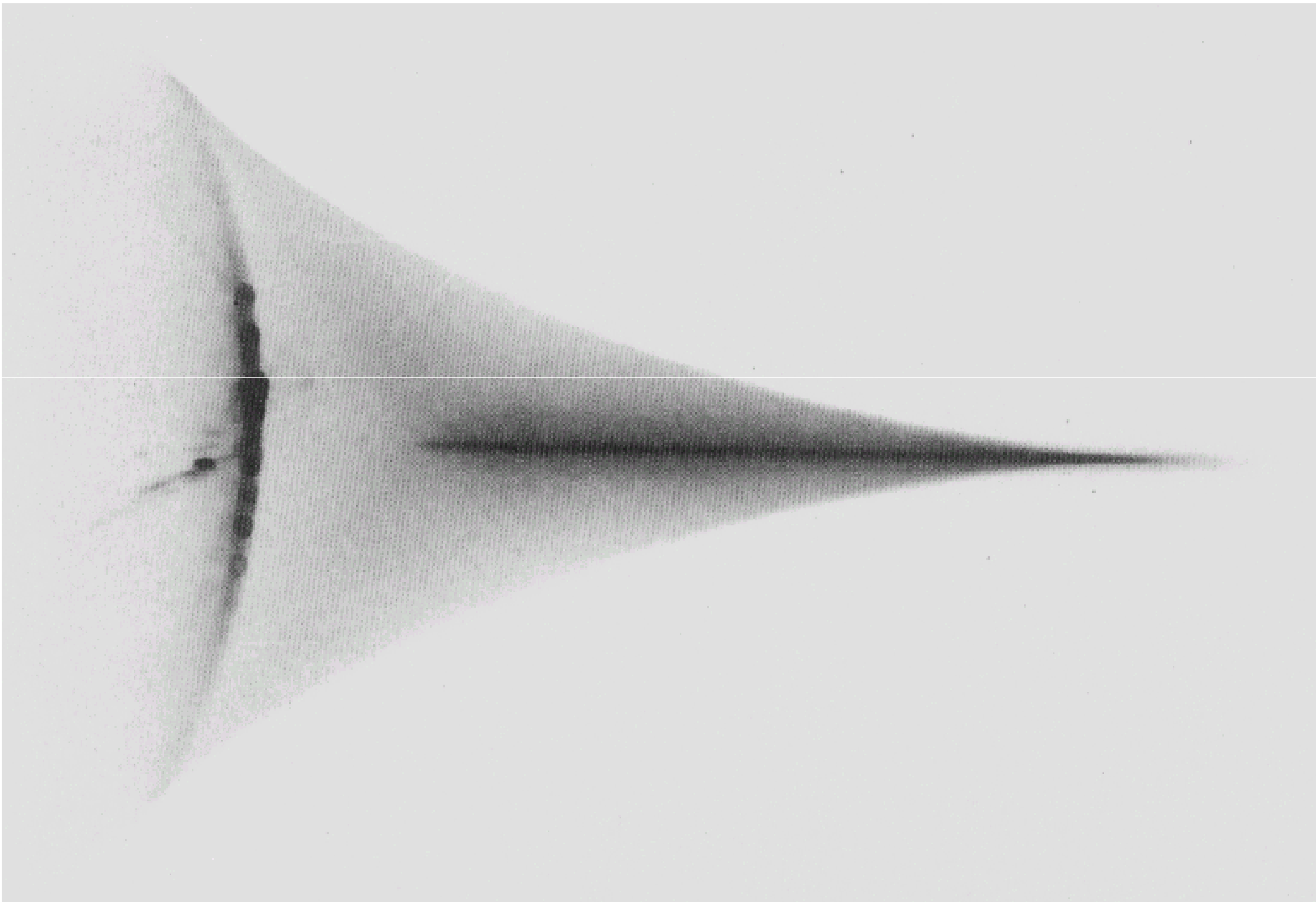
Think of this alignment approach in the following way:

A point source at the CC of *any* aspheric exhibits spherical aberration which yields a caustic. This will include both the caustic horn & more importantly, the axial caustic.

An off-axis piece of that optic still contains a piece of that axial caustic, which by definition, is the optical axis.

All we need to do is take a point source near the CC and superimpose it *anywhere on the axial caustic* and the surface will be aligned!

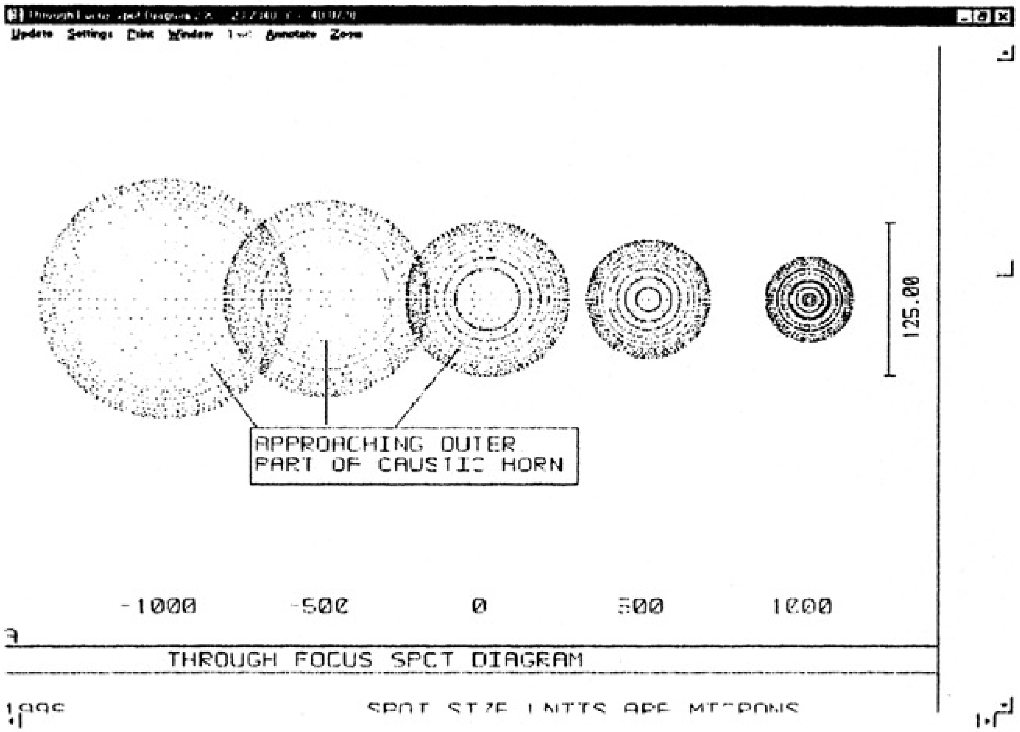
The inner & outer caustic

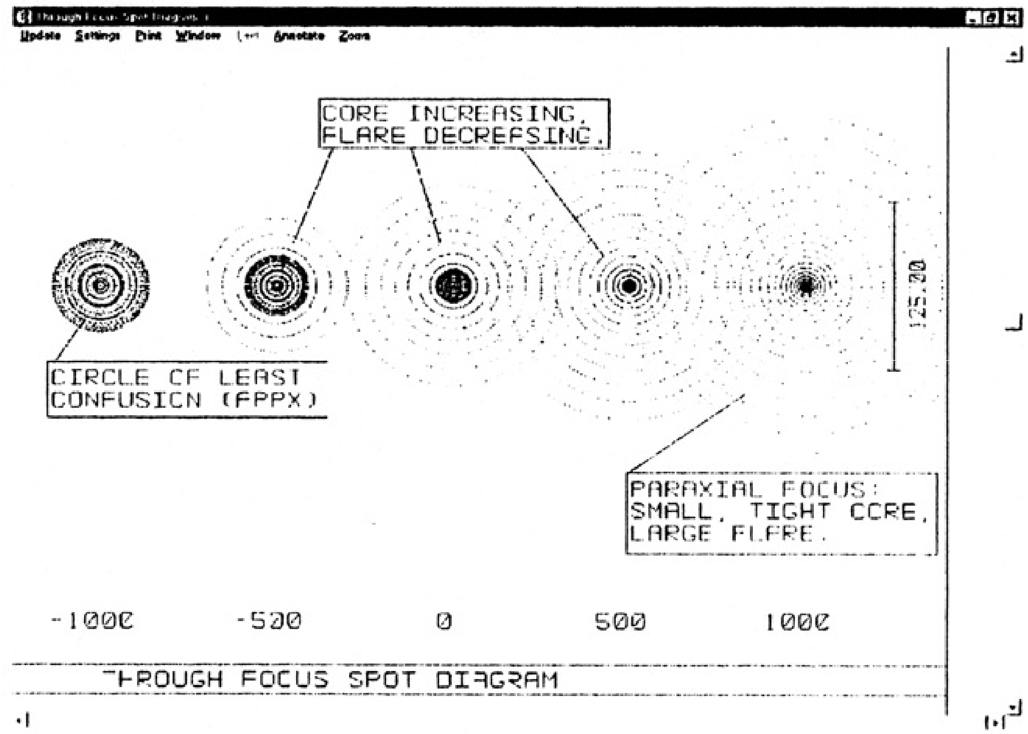


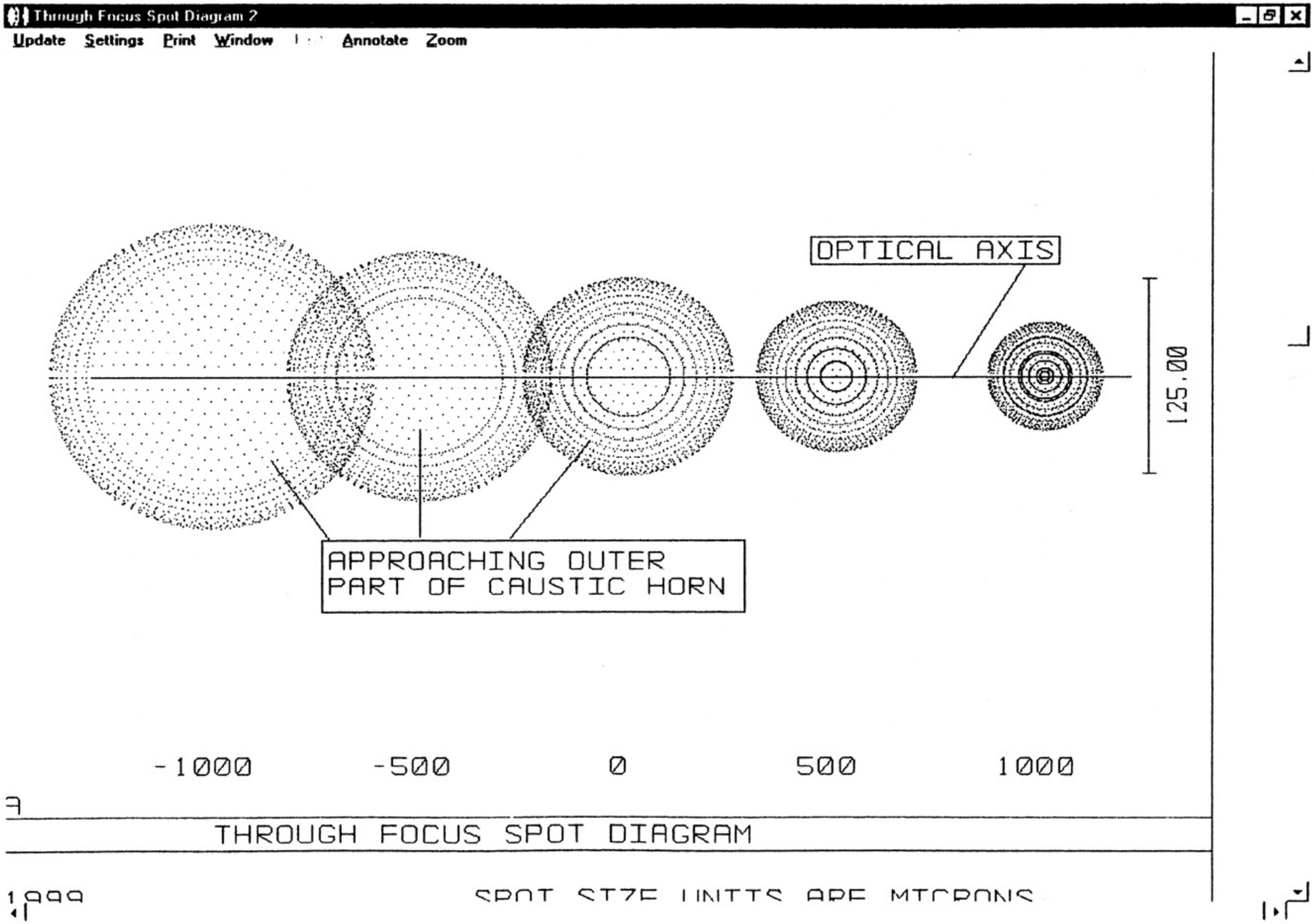
Animation – Thru focus SA3

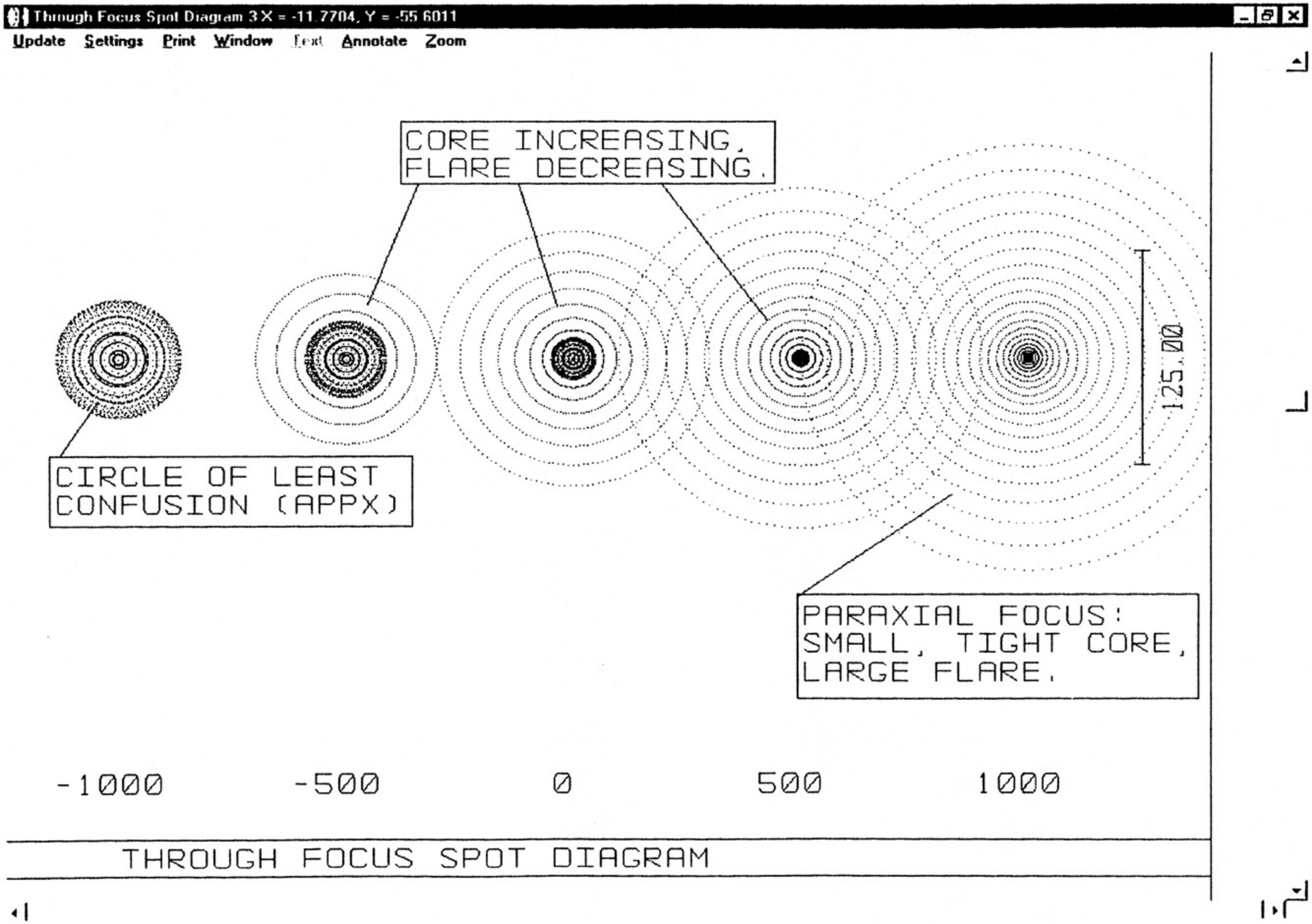
Spot diagrams laced together. Later they will be compared w/spots from the off-axis section

Thru Focus Spots for SA3






Through Focus Spot Diagram 2
Update Settings Print Window Annotate Zoom
OPTICAL AXIS
125.00
APPROACHING OUTER
PART OF CAUSTIC HORN
-1000 -500 0 500 1000
THROUGH FOCUS SPOT DIAGRAM

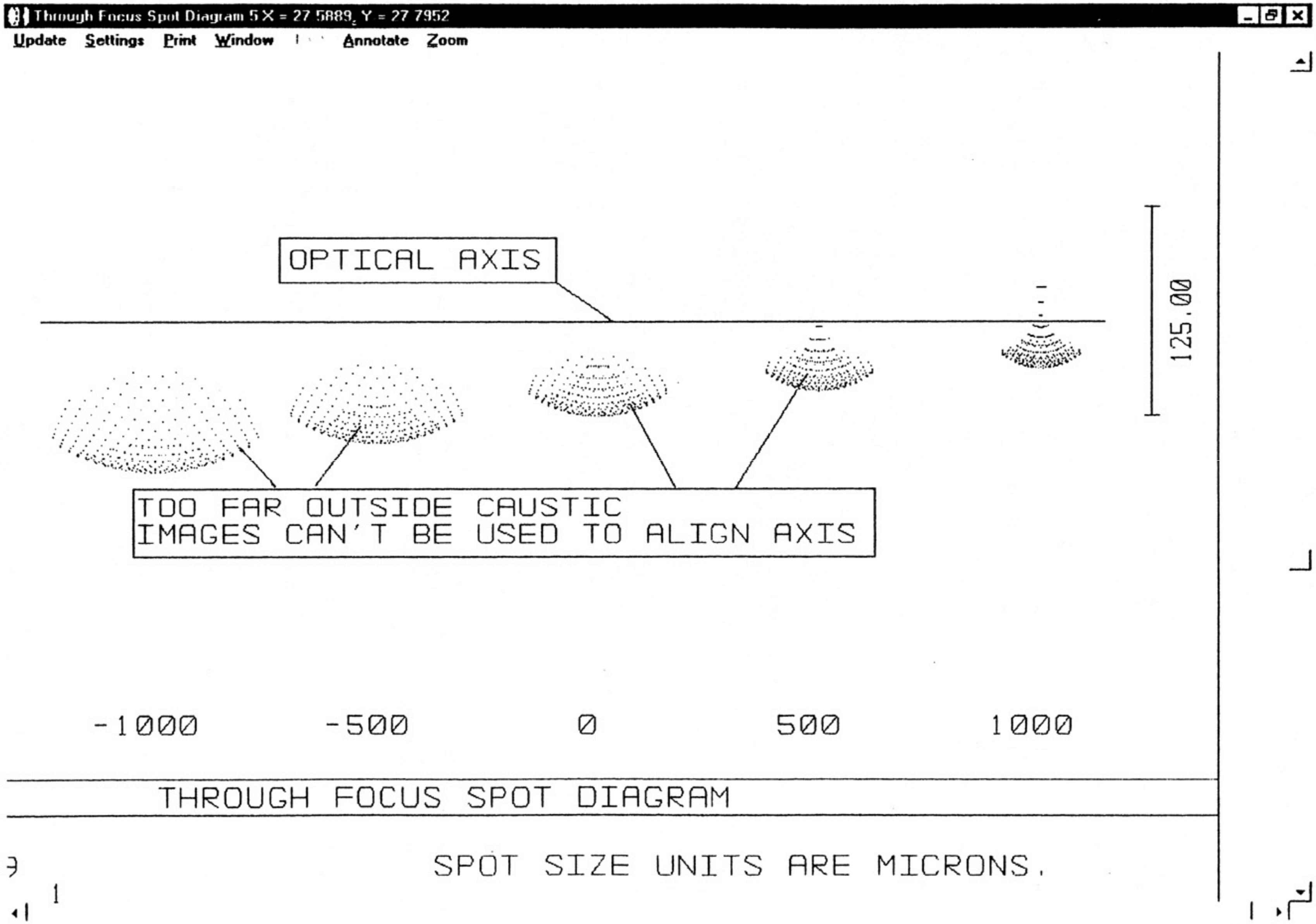

Through Focus Spot Diagram 3 X = -11.7704, Y = -55.6011
Update Settings Print Window Text Annotate Zoom
CORE INCREASING,
FLARE DECREASING.
CIRCLE OF LEAST
CONFUSION (APPX)
PARAXIAL FOCUS:
SMALL, TIGHT CORE,
LARGE FLARE.
125.00
-1000 -500 0 500 1000
THROUGH FOCUS SPOT DIAGRAM

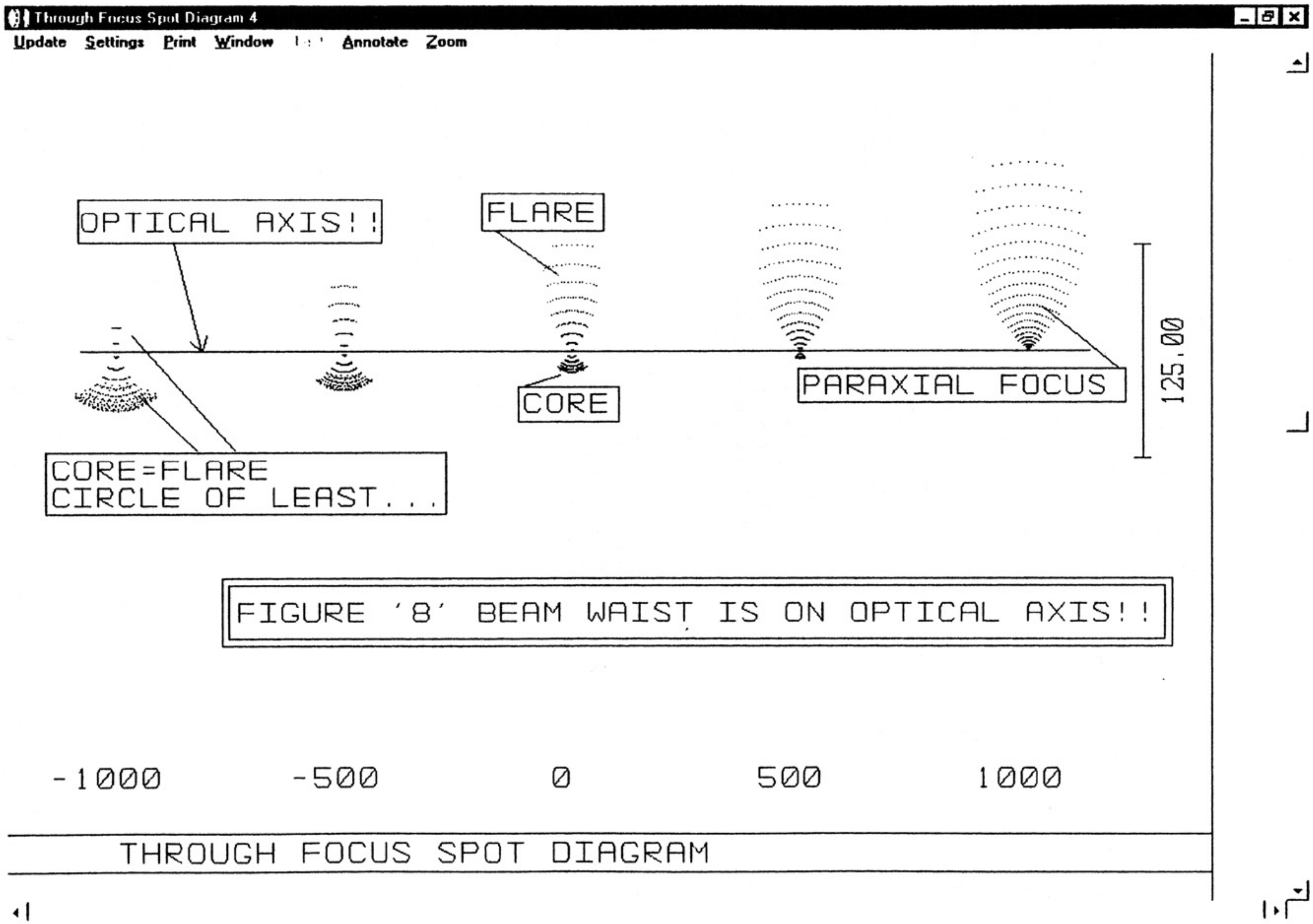
Astigmatism in off-axis SA3

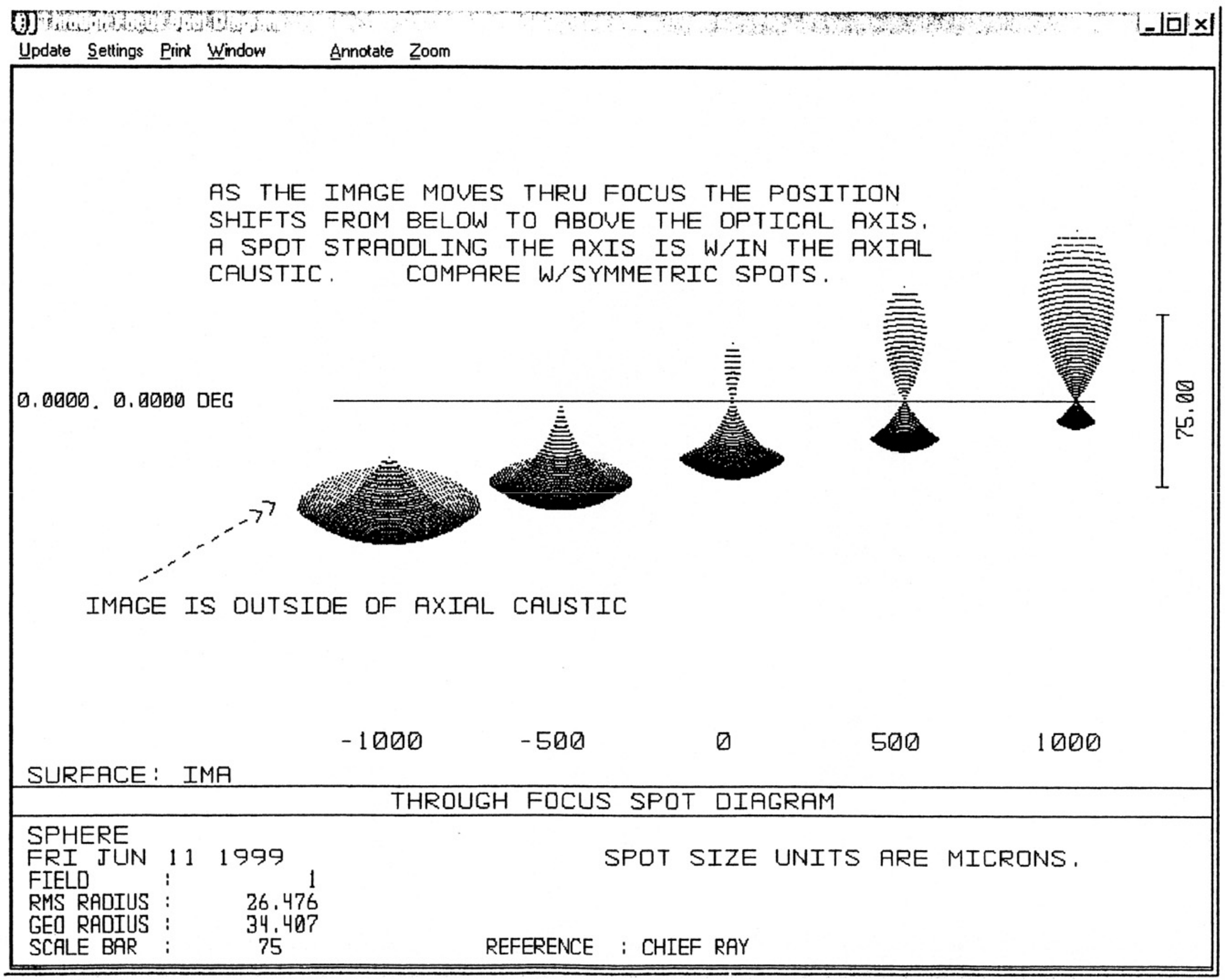
- Everywhere on a sphere the local radii are equal – and in all directions
- If an asphere has changing radii, then they must also be different in both the XZ & YZ planes – this is the definition of astigmatism!
- Where do we find it? On the caustic & in the images.

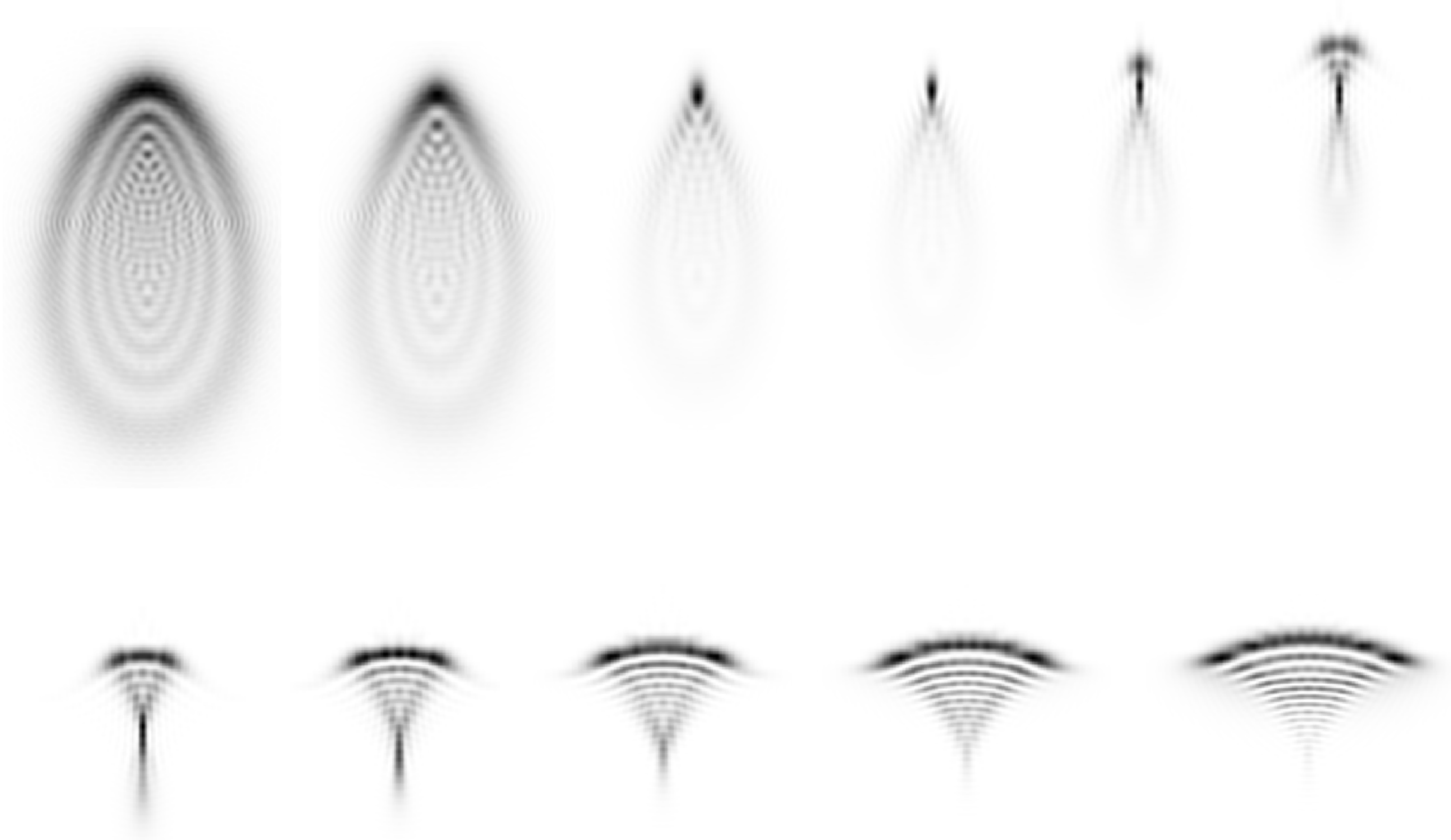
Animation – Thru focus of SA3 from a off-axis section

This is really cool!!


Through Focus Spot Diagram 5 X = 27 5889, Y = 27 7952
Update Settings Print Window Annotate Zoom
OPTICAL AXIS
125.00
TOO FAR OUTSIDE CAUSTIC
IMAGES CAN'T BE USED TO ALIGN AXIS
-1000 -500 0 500 1000
THROUGH FOCUS SPOT DIAGRAM
SPOT SIZE UNITS ARE MICRONS.


Through Focus Spot Diagram 4
Update Settings Print Window Annotate Zoom
OPTICAL AXIS!!
FLARE
CORE
PARAXIAL FOCUS
125.00
CORE=FLARE
CIRCLE OF LEAST...
FIGURE '8' BEAM WAIST IS ON OPTICAL AXIS!!
-1000
-500
0
500
1000
THROUGH FOCUS SPOT DIAGRAM


Update Settings Print Window Annotate Zoom
AS THE IMAGE MOVES THRU FOCUS THE POSITION SHIFTS FROM BELOW TO ABOVE THE OPTICAL AXIS. A SPOT STRADDLING THE AXIS IS W/IN THE AXIAL CAUSTIC. COMPARE W/SYMMETRIC SPOTS.
0.0000, 0.0000 DEG
75.00
IMAGE IS OUTSIDE OF AXIAL CAUSTIC
-1000
-500
0
500
1000
SURFACE: IMA
THROUGH FOCUS SPOT DIAGRAM
SPHERE
FRI JUN 11 1999
FIELD : 1
RMS RADIUS : 26.476
GEO RADIUS : 34.407
SCALE BAR : 75
SPOT SIZE UNITS ARE MICRONS.
REFERENCE : CHIEF RAY

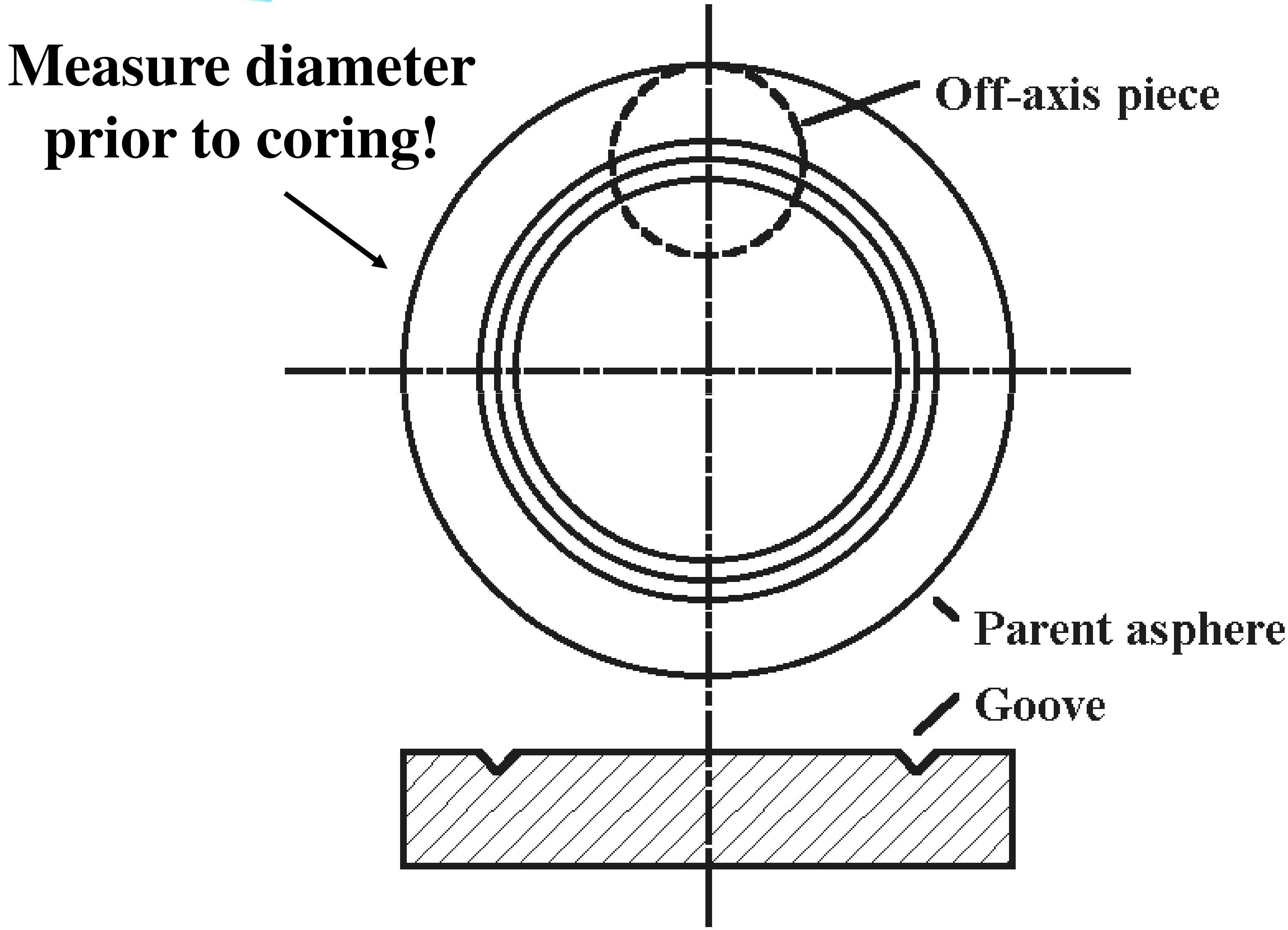


Thru focus diffraction images of off-axis spherical aberration

Preparation of the parent

- What can be done to the parent aspheric surface prior to coring (or cutting) out the section?
- How do we locate the parent vertex of the section after coring?

Preparing the parent for coring

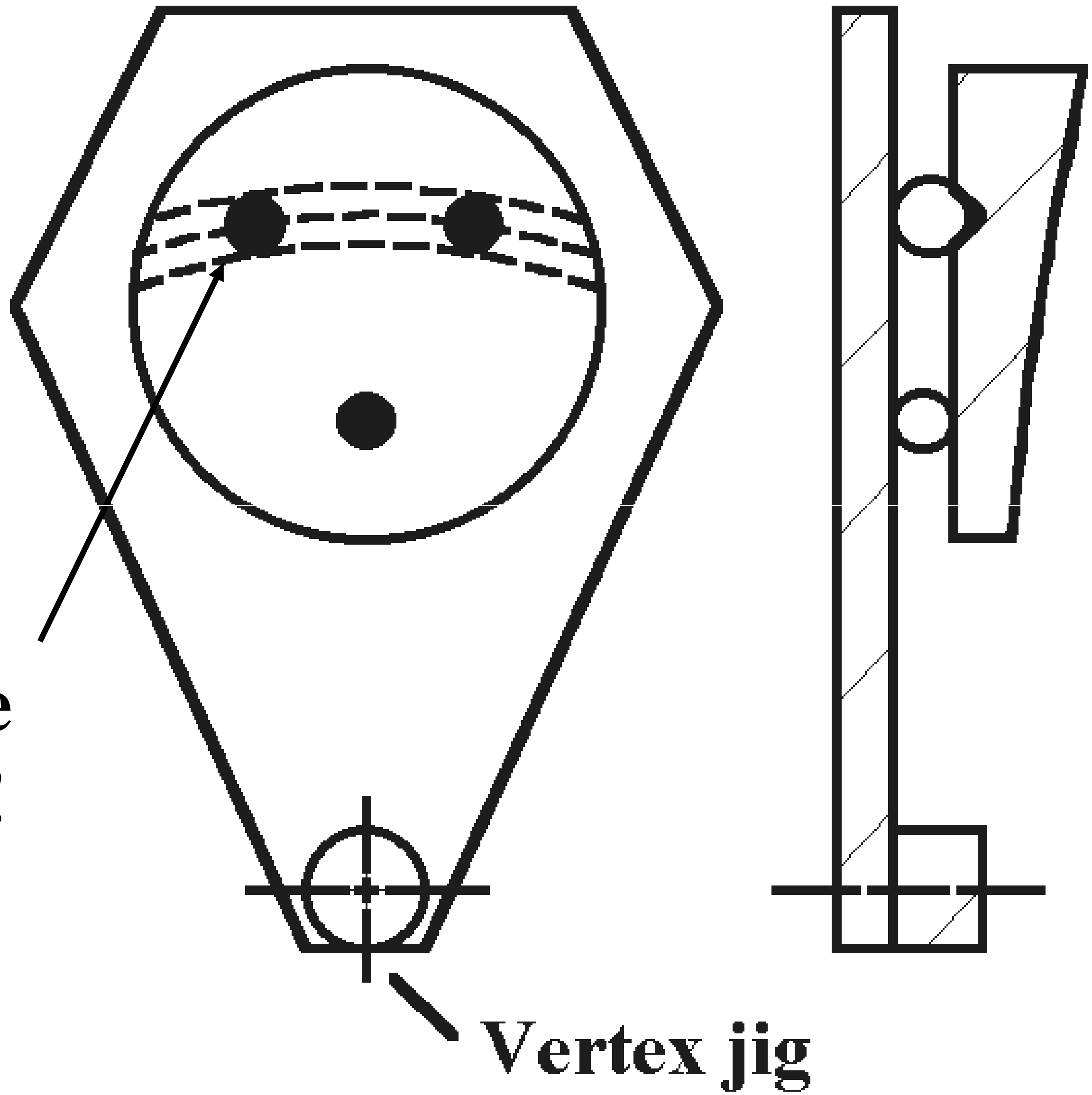


The vertex jig

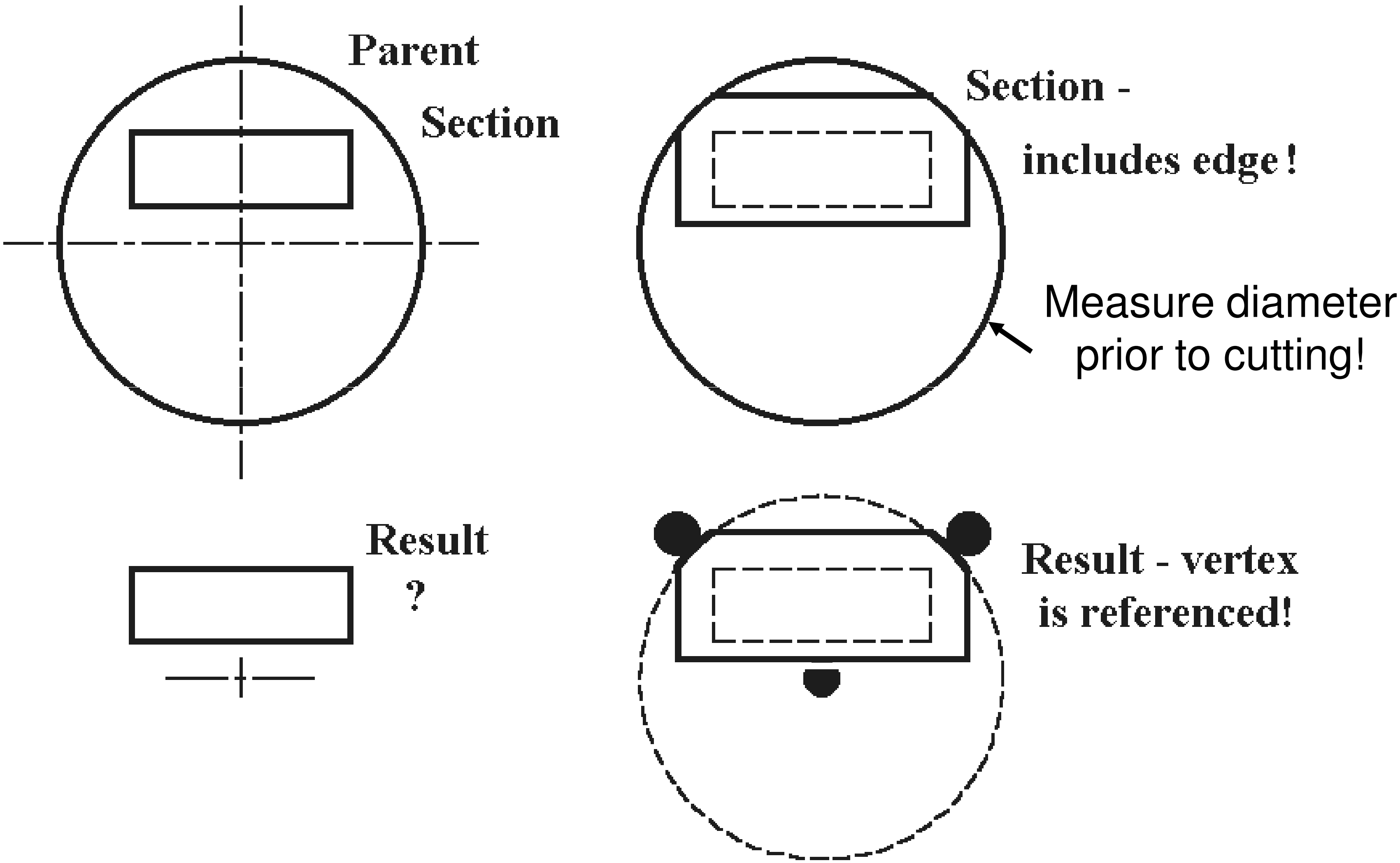
<u>3-ball mount</u>

2 balls in groove

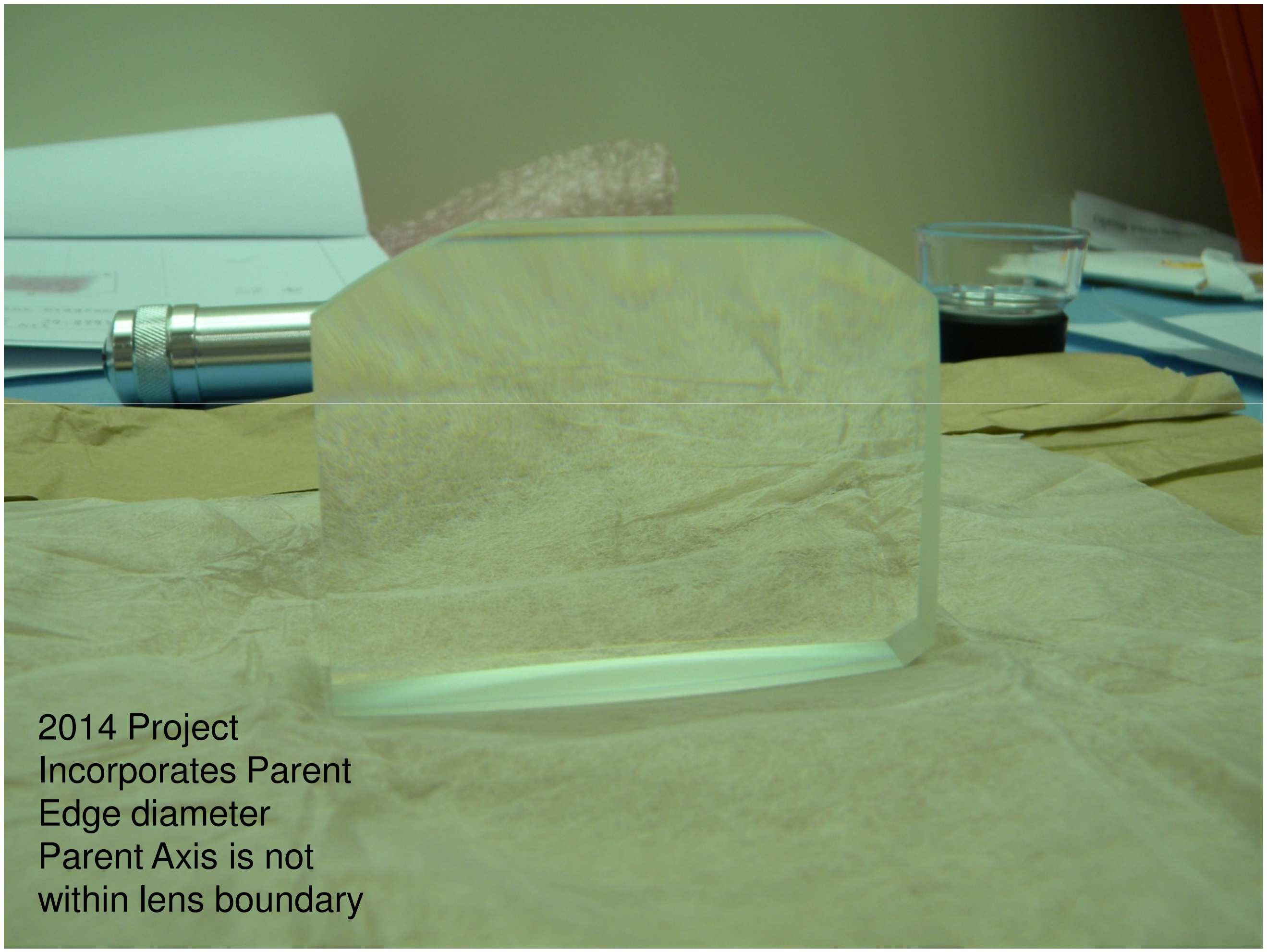
Clock rotation!!



Cutting a rectangular section



Aspheric Off-Axis Lens Section



2014 Project
Incorporates Parent
Edge diameter
Parent Axis is not
within lens boundary