5.0 Alignment of Off-axis Optics

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 ≠ -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, $\kappa$; higher order aspheric coefficients $A, B, C, \ldots$
- 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).

Paraxial center of curvature

Focal point
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 \( \infty \) 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 \( \infty \) 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.

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Gut ray

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Surface axis

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 \( \Rightarrow \) changes position
- Tip/tilt changes decenter \( \Rightarrow \Delta \) 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

- Core Increasing
- Flare Decreasing
- Circle of Least Confusion (FPPX)
- Paraxial Focus: Small, Tight Core, Large Flare

Through Focus Spot Diagram

Spot size units are microns
APPROACHING OUTER PART OF CAUSTIC HORN

OPTICAL AXIS

THROUGH FOCUS SPOT DIAGRAM

SPOT SIZE UNITS ARE MICRONS
CORE INCREASING, FLARE DECREASING.

CIRCLE OF LEAST CONFUSION (APPX)

PARAXIAL FOCUS: SMALL, TIGHT CORE, LARGE FLARE.

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!!
Optical Axis

Too far outside caustic images can't be used to align axis

Through Focus Spot Diagram

Spot size units are microns.
**Optical Axis!!**

**Flare**

**Core = Flare**

**Circle of Least...**

**Figure '8' Beam Waist is on Optical Axis!!**

**Through Focus Spot Diagram**
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

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

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

Measure diameter prior to coring!

Off-axis piece

Parent asphere

Groove
The vertex jig

3-ball mount
2 balls in groove
Clock rotation!!
Cutting a rectangular section

Measure diameter prior to cutting!

Section - includes edge!

Result - vertex is referenced!
Aspheric Off-Axis Lens Section

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