Starting Points for Designing Freeform Four-Mirror Telescopes

Jonathan Papa

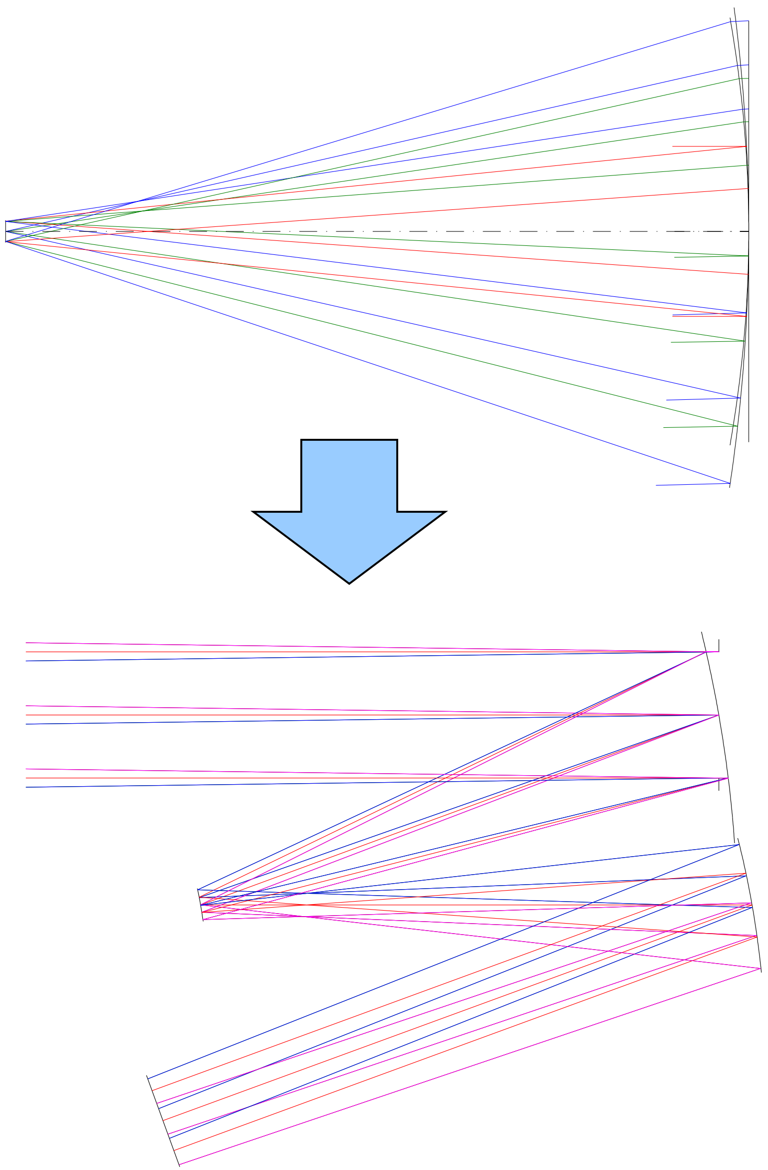
Jannick Rolland (PI)

Joseph Howard (NASA mentor)

Project Overview

- Central Objective: Survey of the four-mirror freeform solution space that considers geometries that could be advantageous for system constraints, such as mass, volume, stray light control, or radiation shielding.

- Methods/Techniques: Use analytically designed starting points before adding freeform terms to explore different design forms.



Parts of the Design Process

Selection of Suitable Starting Point

Investigate multiple starting point design methods with the goal of finding as many unique design forms as possible.

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Optimization Techniques

Investigate multiple optimization approaches.

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Tolerancing/Sensitivity Analysis

Compare sensitivity across the different design forms.

Considered Starting Points So Far (This is not an exhaustive list)

Method	Corrected through 3rd Order	Stigmatic Imaging at Every Surface (One Field Point)	Unobscured
Rotationally-Symmetric Rakich All-Spherical Maps	●		
Rotationally-Symmetric All-Conic Maps	●	●	
Off-Axis Conic Layout Tool		●	●
Off-Axis Conics from Aberration Coefficients for Plane-Symmetry	●	●	●

Starting Points

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Rotationally-Symmetric Rakich All-Spherical Maps

$$W_{spherical} = -\frac{1}{8}\, n^2\, {i_a}^2\, y_a \left(\frac{{u_a}'}{n'} - \frac{u_a}{n} \right)$$

$$Total\ Spherical\ Aberration = \sum_i W_i$$

$$Total\ Coma \propto \sum_i x_i\, W_i$$

$$Total\ Astigmatism \propto \sum_i {x_i}^2\, W_i$$

To get an anastigmat solution, the following conditions must be satisfied:

$$W_1 + W_2 + W_3 + W_4 = 0$$
$$W_1\, x_1 + W_2\, x_2 + W_3\, x_3 + W_4\, x_4 = 0$$
$$W_1\, {x_1}^2 + W_2\, {x_2}^2 + W_3\, {x_3}^2 + W_4\, {x_4}^2 = 0$$

Rakich solves for the curvature of mirrors 3 and 4; and the thicknesses after mirrors 2, 3, and 4; as a function of the curvature of mirror 2, the thickness after mirror 1, and stop location x1.

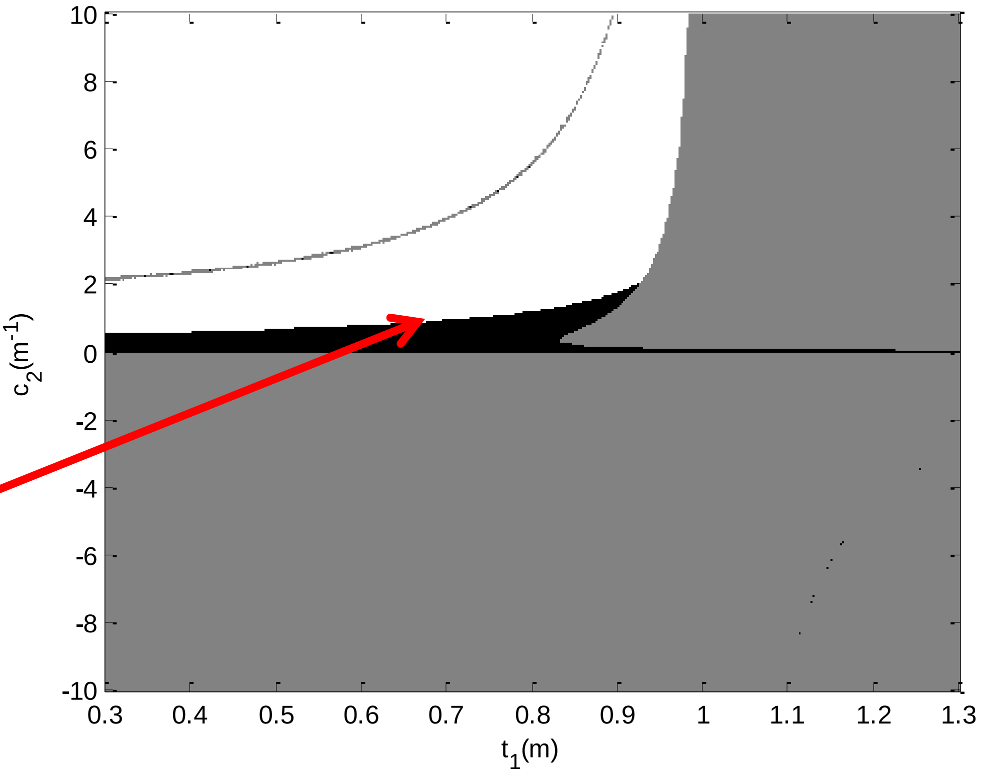
Rakich, Opt. Eng. 46(10), 2007

Rotationally-Symmetric Rakich All-Spherical Maps

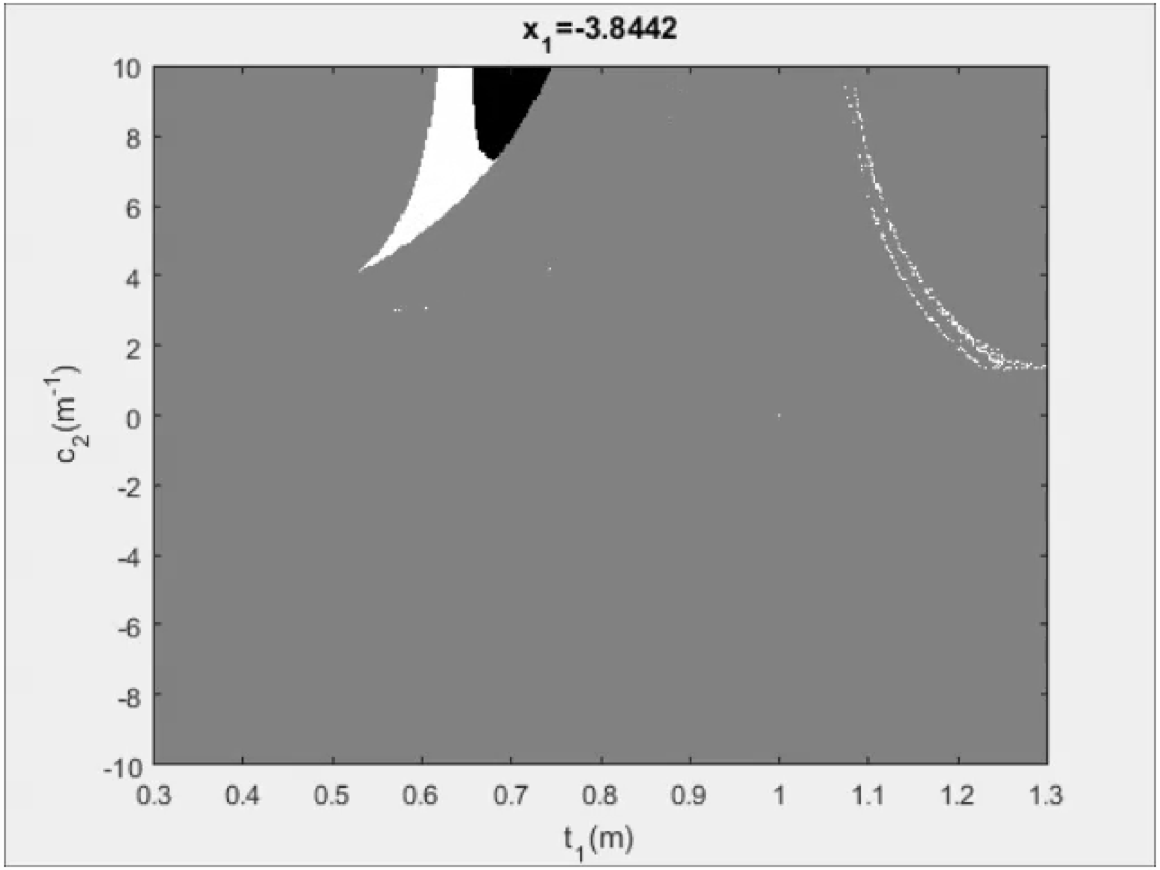
Matlab Implementation: Parameters of the three dimensional solution space are t1 (thickness after mirror 1), c2 (curvature of mirror 2), and x_1 (represented as time axis of video, corresponds to stop position).

Interface = Flat Field Solutions

White: >0 PZT; Black: <0 PZT; Gray: No Viable solution



Video of Solution Space



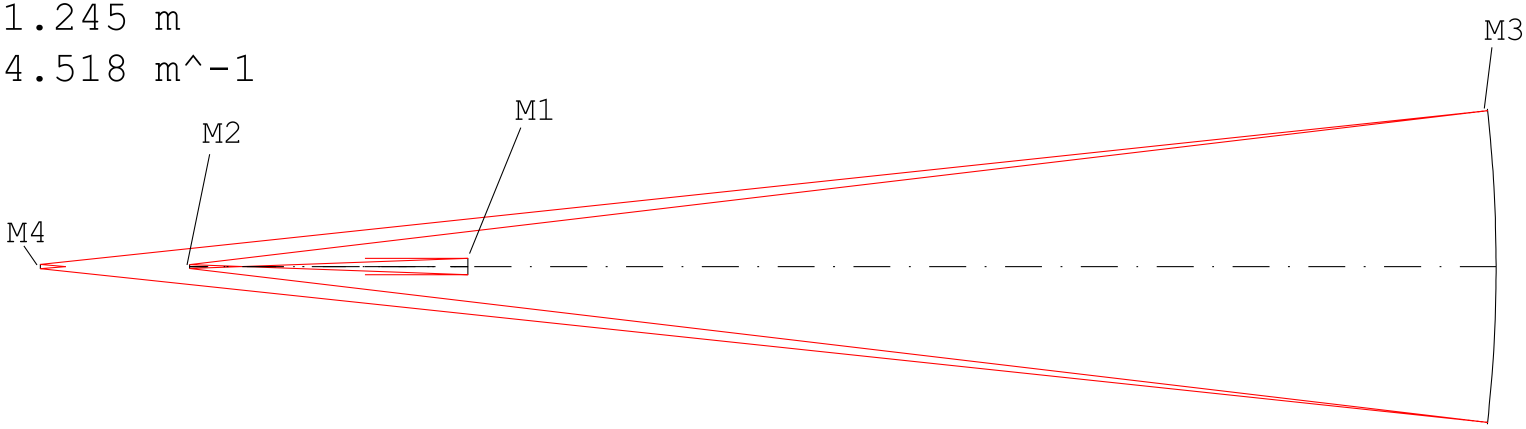
Rotationally-Symmetric Rakich All-Spherical Maps

- Pick a solution from the solution map by filtering for solutions with desirable properties; such as adequate mirror separations that allow for unobscuration by using smaller tilts, or internal images, etc.

- Unobscure by tilting the mirrors while adding freeform terms (i.e. Zernikes) through optimization.

Validation of Solution Maps

Parameters:
Cubic 1: solution 2
Cubic 2: solution 3
x1=2
t1=1.245 m
c2=4.518 m^-1



FMA

Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ
STO	0.002646	0.000996	0.000083	0.000000	-0.000042	0.000000	0.000000	0.000000	0.001000
2	-0.025482	-0.015082	-0.002599	-0.000615	0.000377	-0.000121	0.000000	0.000000	-0.009036
3	0.033775	0.022323	0.004904	0.001626	-0.000013	0.000358	0.000000	0.000000	0.000320
4	-0.010939	-0.008236	-0.001972	-0.000594	0.000095	-0.000149	0.000000	0.000000	-0.002291
SUM	0.000000	0.000000	0.000417	0.000417	0.000417	0.000088	0.000000	0.000000	-0.010007

781.25 MM

FMA Scale: 0.03 JCP 31-Mar-16

Starting Points

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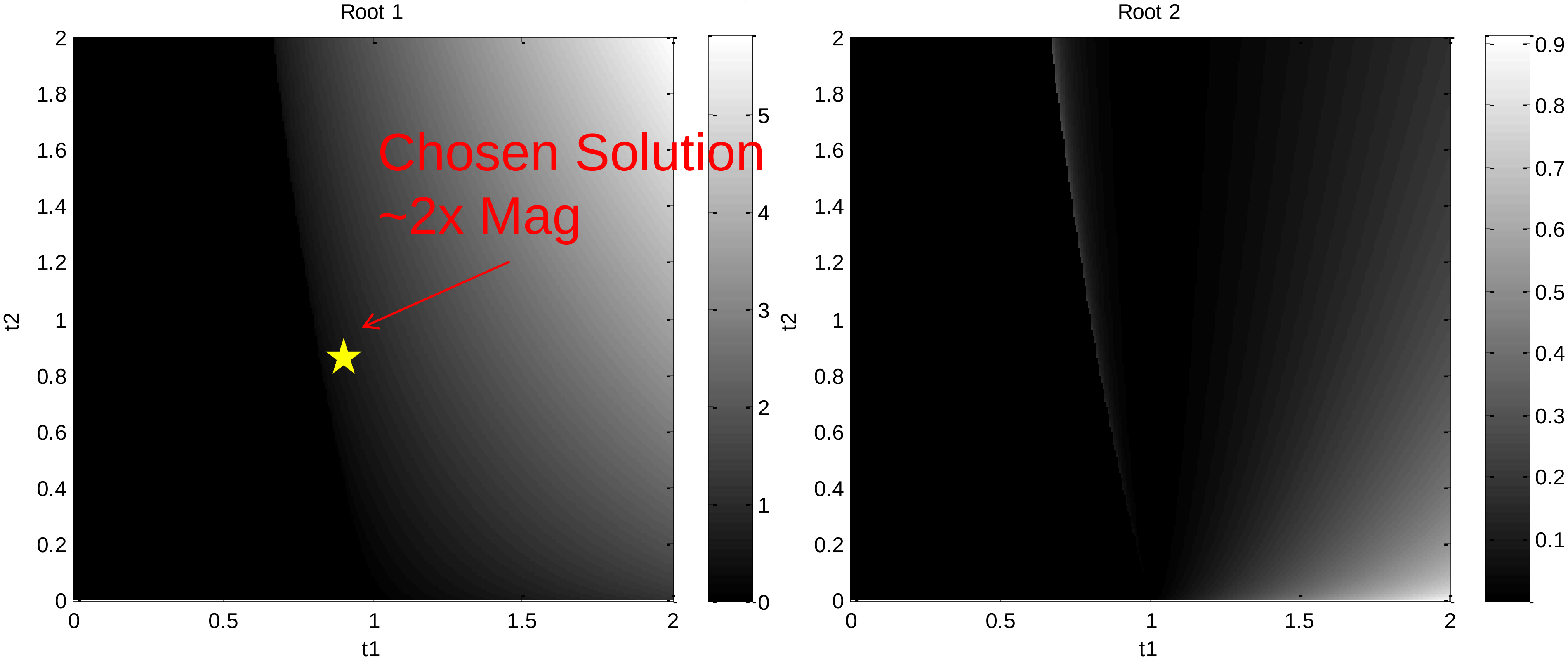
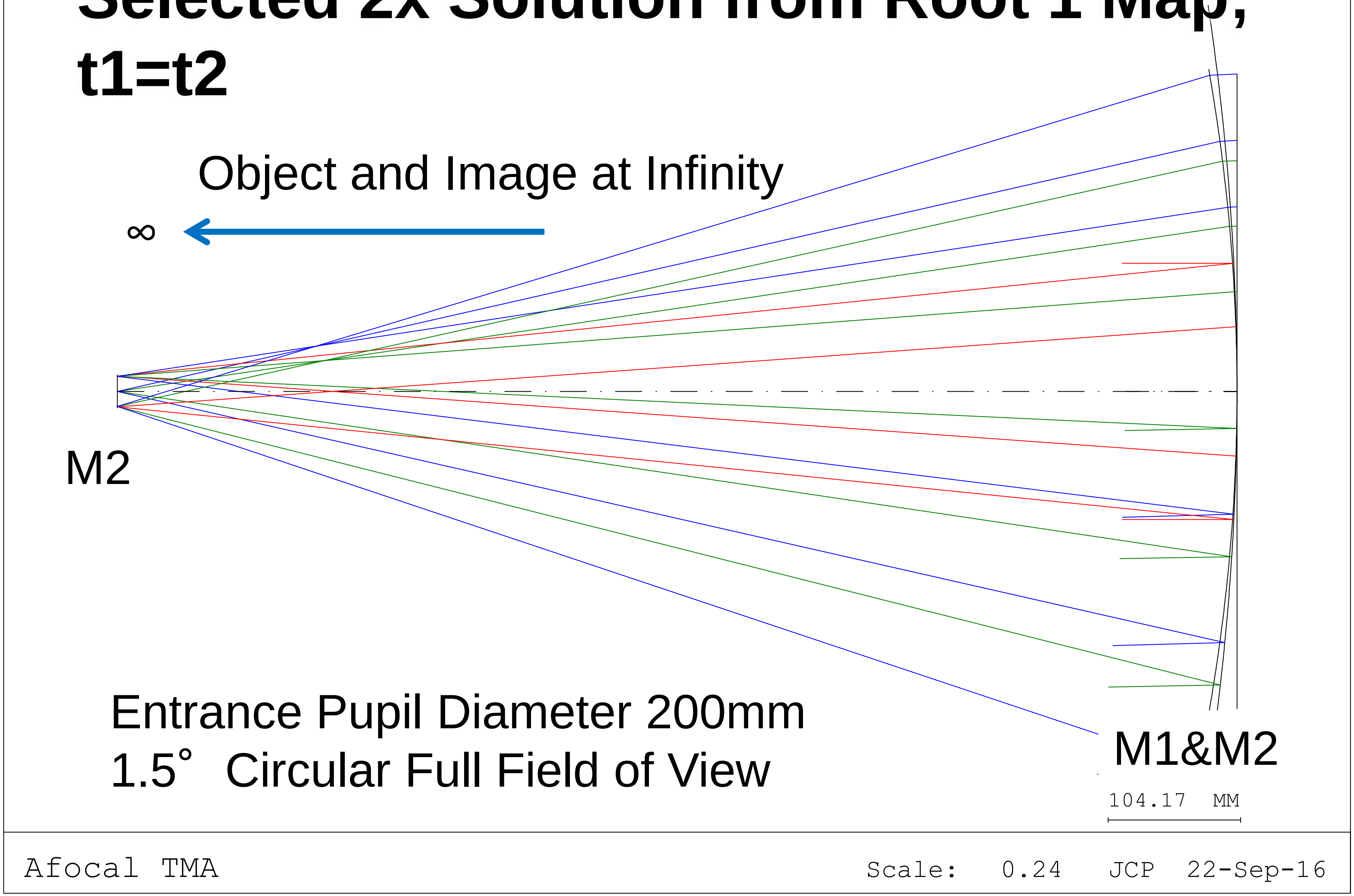
Off-Axis Conic Layout Tool		●	●
Off-Axis Conics from Aberration Coefficients for Plane-Symmetry	●	●	●

Rotationally-Symmetric All-Conic Maps for Afocal Three Mirror Systems

- Grayscale represents magnification.
- Focal length of primary set to 1.
- Assuming positive primary.



Selected 2x Solution from Root 1 Map; t1=t2



Entrance Pupil Diameter 200mm

1.5° Circular Full Field of View

Third Order Analysis

Afocal TMA

Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.247594	1.812133	-4.353068	-1.405749	0.067910	3.429543
	0.247594	-1.423124	2.726615	0.908872		-1.741340
STO	0.025215	-0.192614	0.326974	0.000000	-0.163487	0.000000
	-0.025215	0.000000	0.000000	0.000000		0.000000
3	-0.044840	0.314107	-0.637873	-0.148907	0.095577	0.347702
	0.044840	-0.510502	1.937353	0.645784		-2.450749
SUM	0.000000	0.000000	0.000000	0.000000	0.000000	-0.414845

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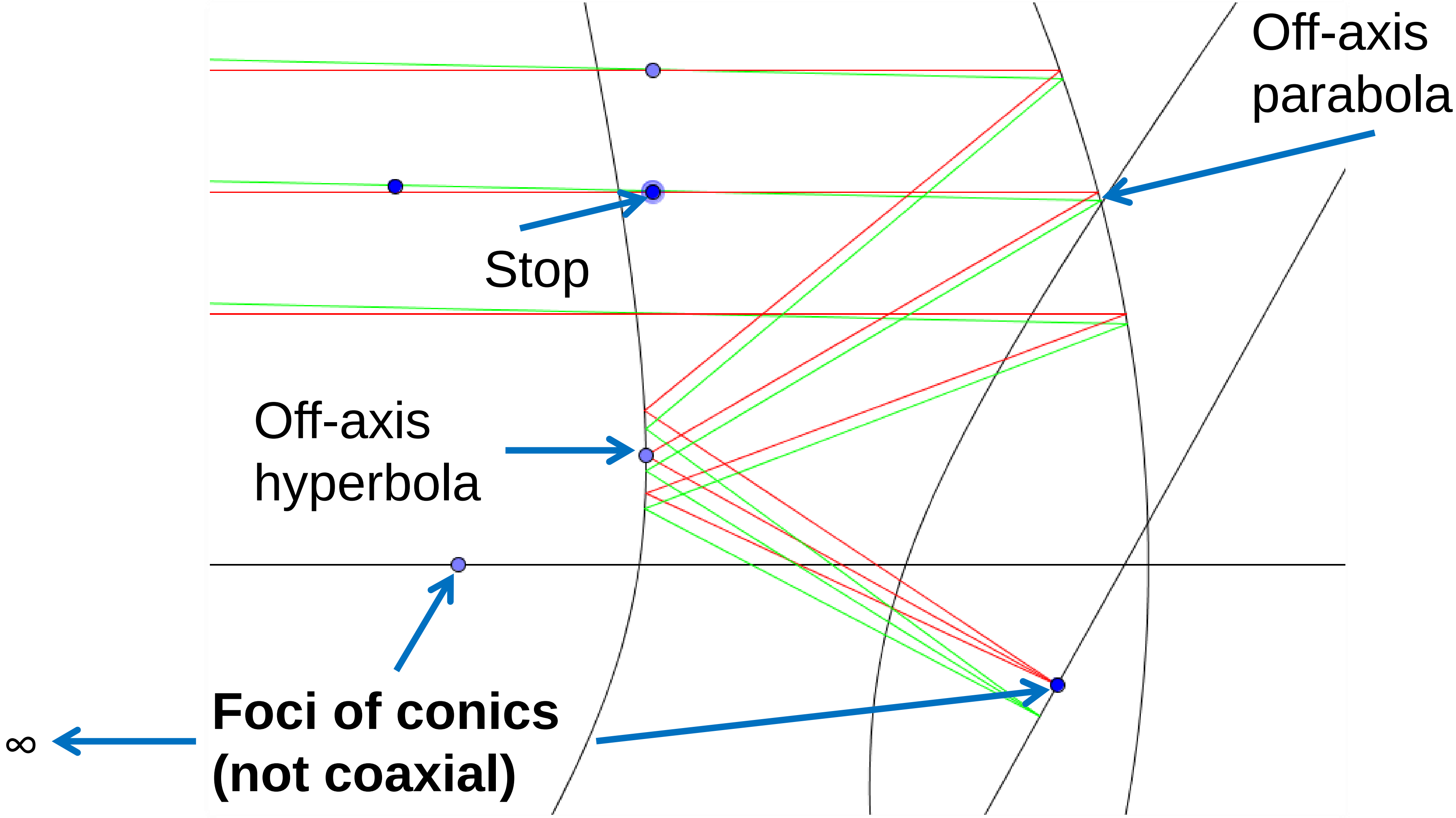
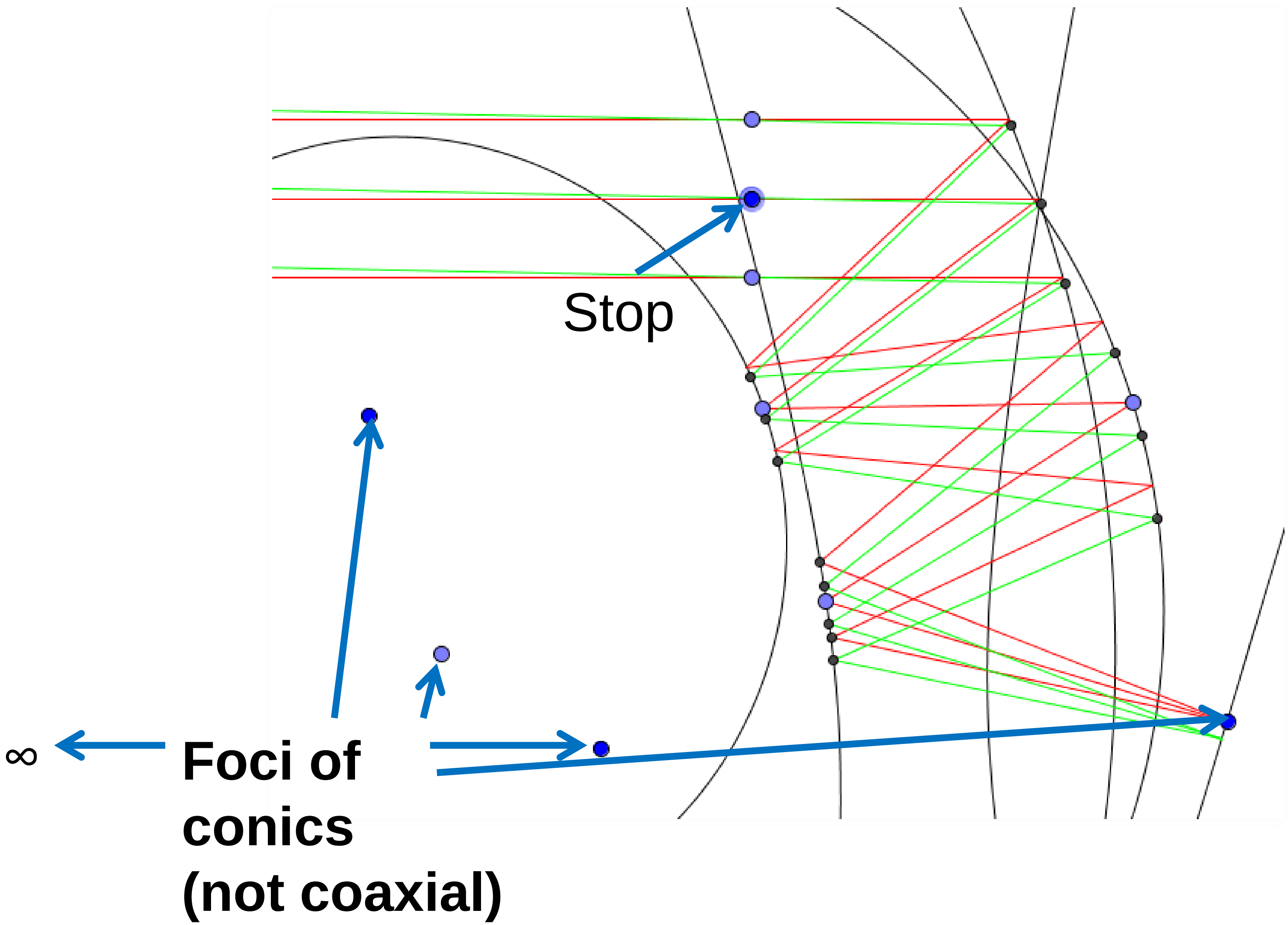
Off-Axis Conic Layout Tool

- Force stigmatic imaging for the field point along optical axis ray (OAR)/base ray, such that all intermediate image points are stigmatic, allow “pivoting” about the foci of the conics. System is like a linkage of off-axis conic mirrors.
- When pivoting, the basal field point remains stigmatic.
- This method allows for **unobscured** starting points.

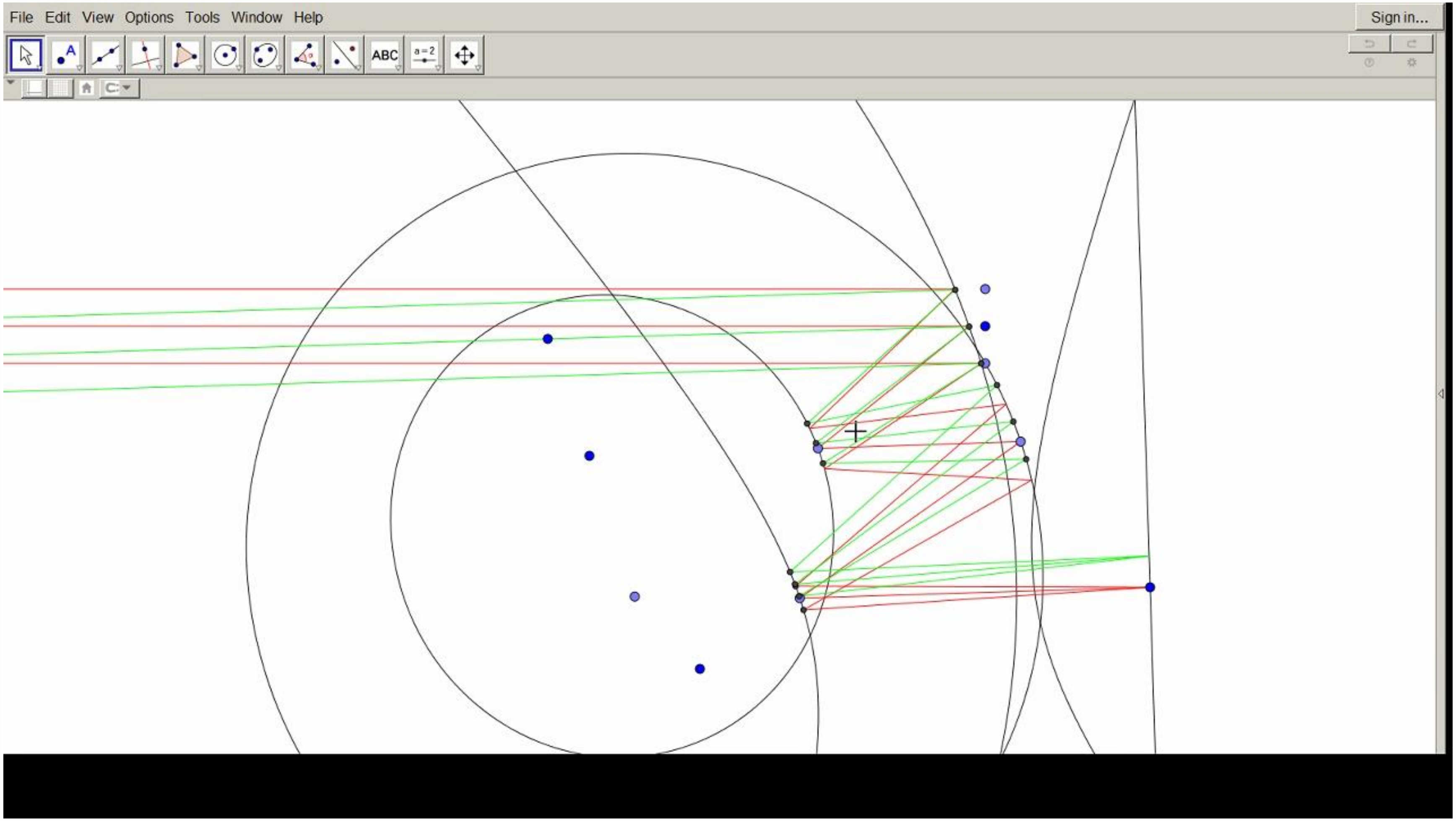
Two Mirror Pivoting Conics



Four Mirror Pivoting Conics



Video of Off-Axis Conic Layout Tool



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Off-Axis Conics from Aberration Coefficients for Plane-Symmetry

- All conic foci are constrained to a plane.

- Sasian developed aberration coefficients for plane-symmetric systems that depend on paraxial raytrace quantities to third order. He demonstrated the coefficients on a two mirror system pivoting about shared conic focus.

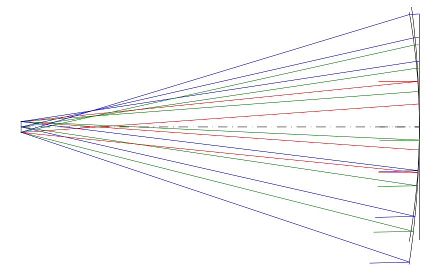
- **This method will utilize the solutions from the "Rotationally-Symmetric All-Conic Maps" method, and take it further by unobscuring those solutions (like in the "Off-Axis Conic Layout Tool", but this method is corrected through 3rd order instead of just at one field point).**

Sasian, Opt. Eng. 33(6), 1994

Aberration Coefficients Before and After Tilting/Unobscuring

In waves zero-to-peak at 587.5618 nm; before tilting

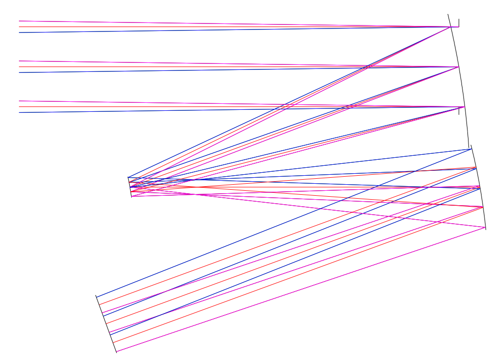
Aberrations	Surface 1	Surface 2	Surface 3	Sum
Linear Coma	-5.57	2.76	2.81	0.00
Field Lin. Field Asym. Ast.	0.00	0.00	0.00	0.00
Quadratic Astigmatism	1.46	1.77	-3.23	0.00
Field Curvature	0.00	2.64	-2.64	0.00

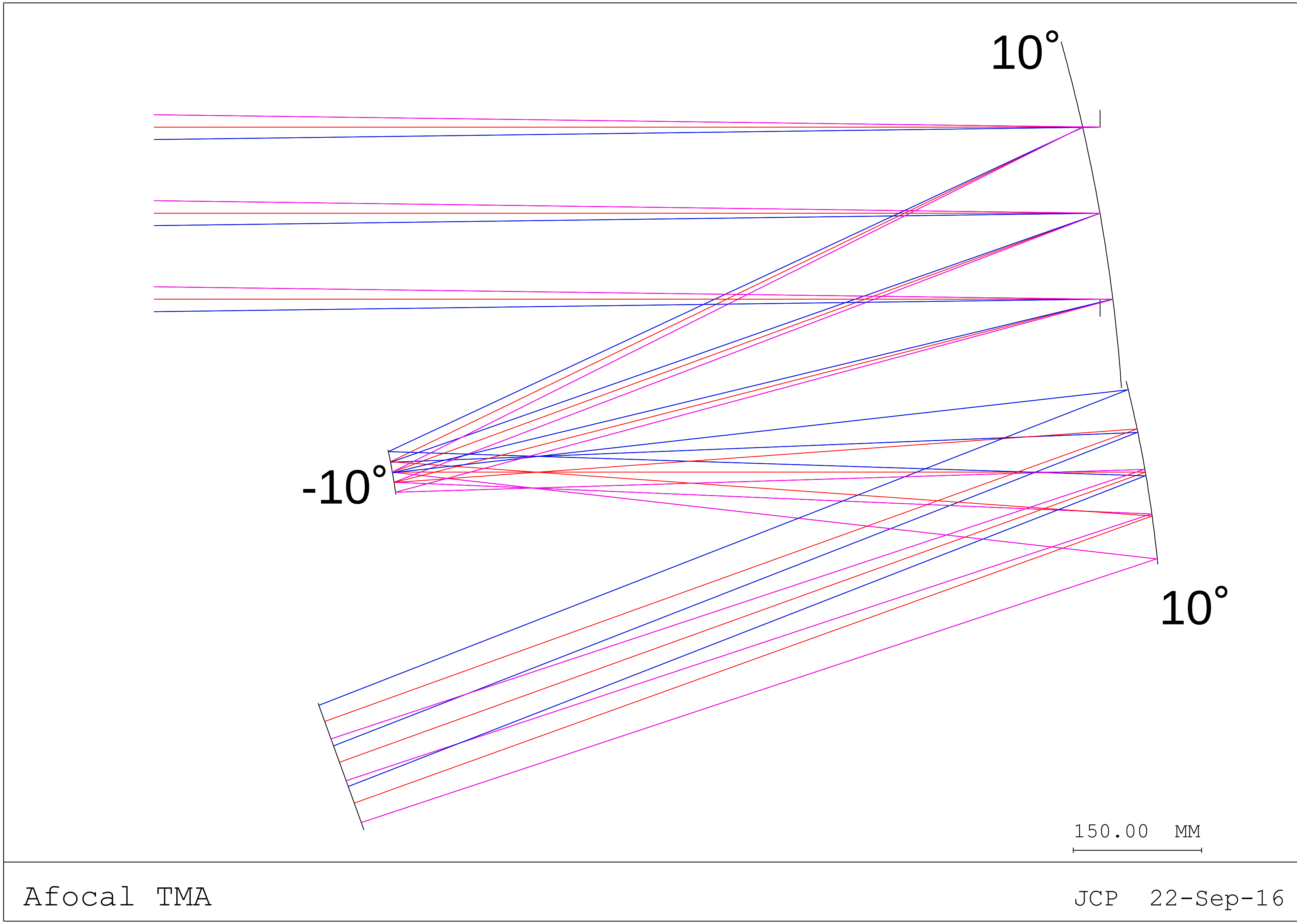


Tilt mirrors to unobscure while canceling introduced linear astigmatism, as we tilt.

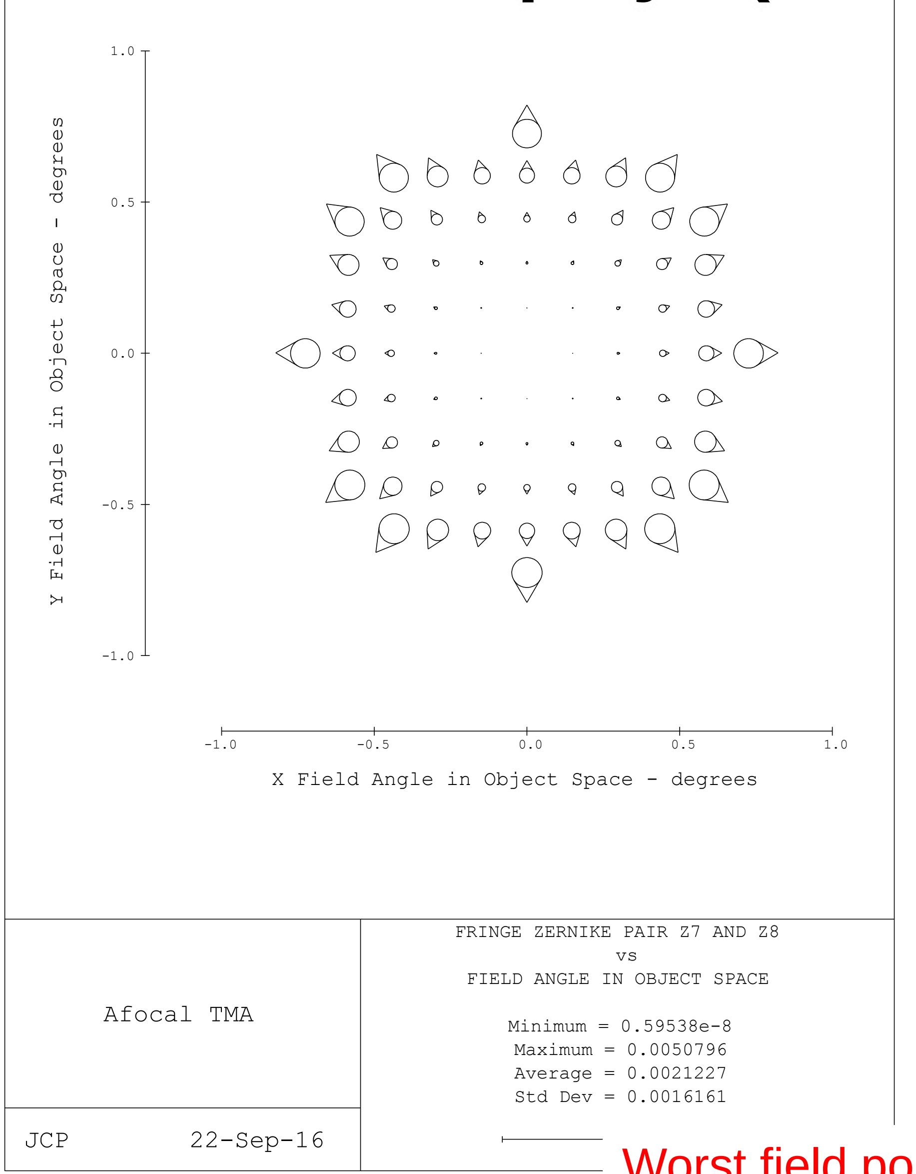
	Surface 1	Surface 2	Surface 3
Tilt	10°	-10°	10°

Aberrations	Surface 1	Surface 2	Surface 3	Sum
Linear Coma	-5.49	2.76	2.85	0.13
Field Lin. Field Asym. Ast.	38.69	-11.20	-27.49	0.00
Quadratic Astigmatism	1.46	1.79	-3.31	-0.07
Field Curvature	0.01	2.62	-2.67	-0.03

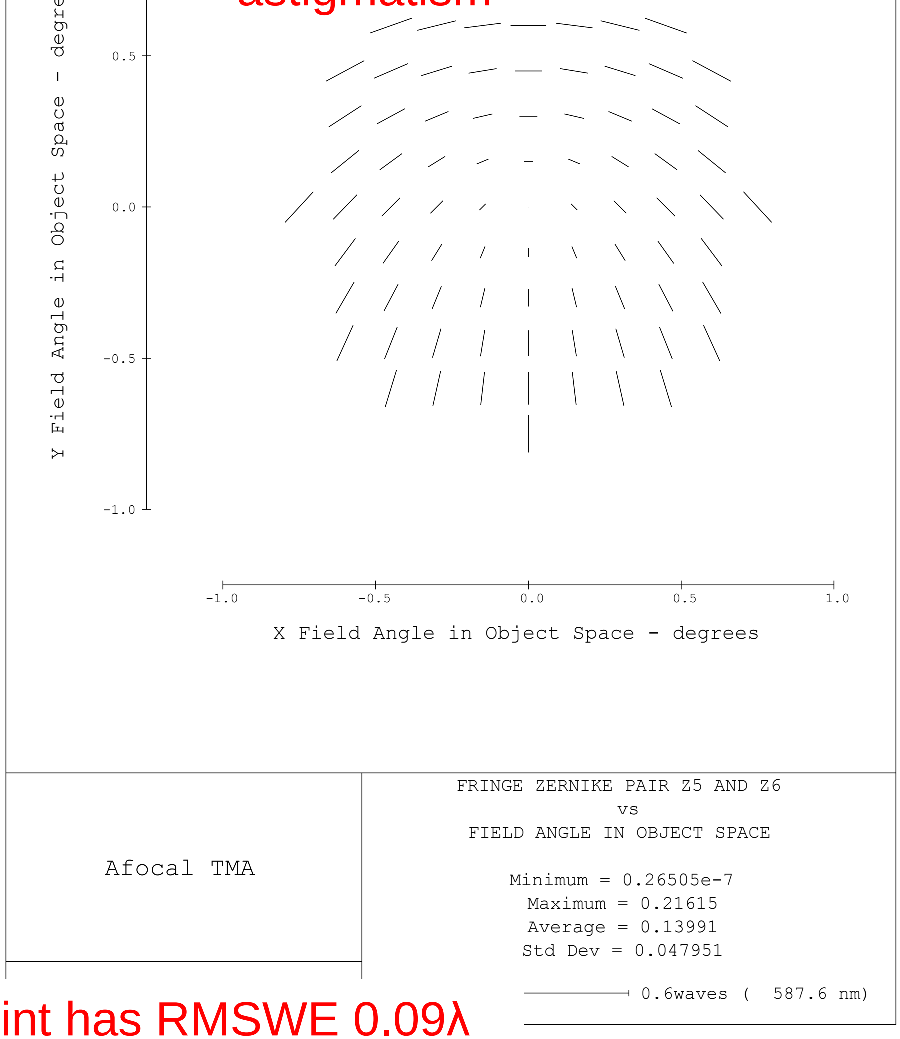



10°
-10°
10°
150.00 MM
Afocal TMA
JCP 22-Sep-16

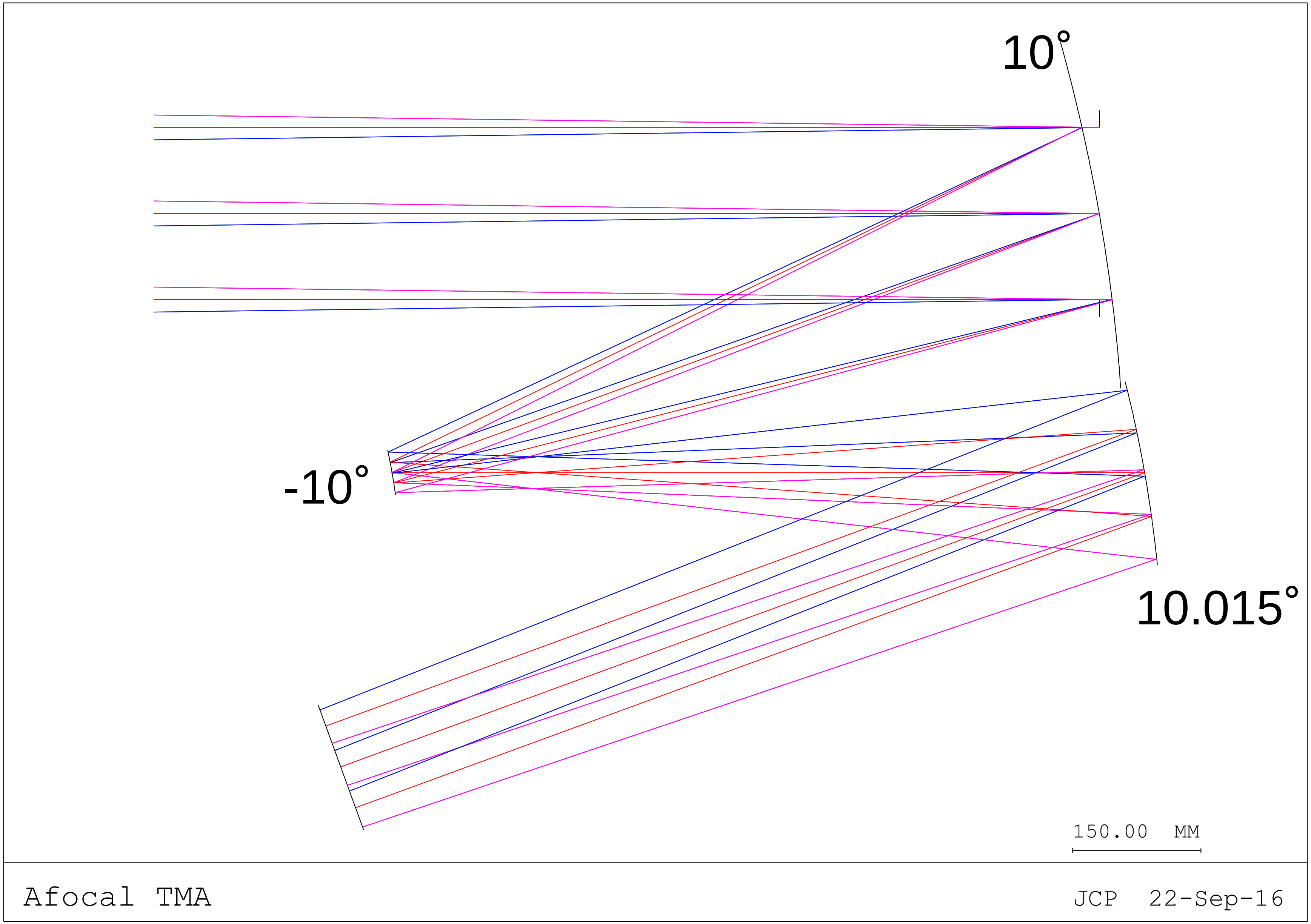
Full Field Displays (Real Raytracing)

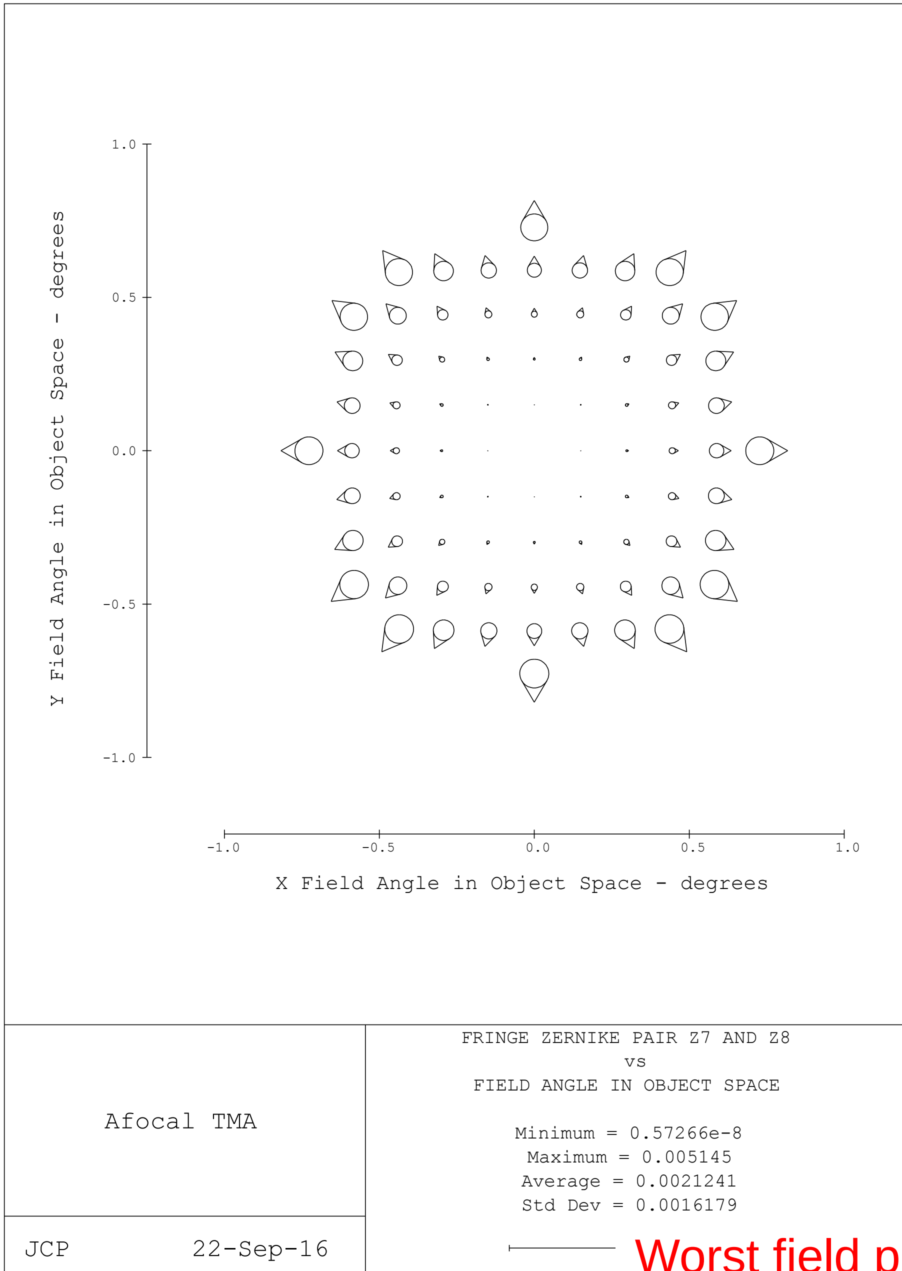


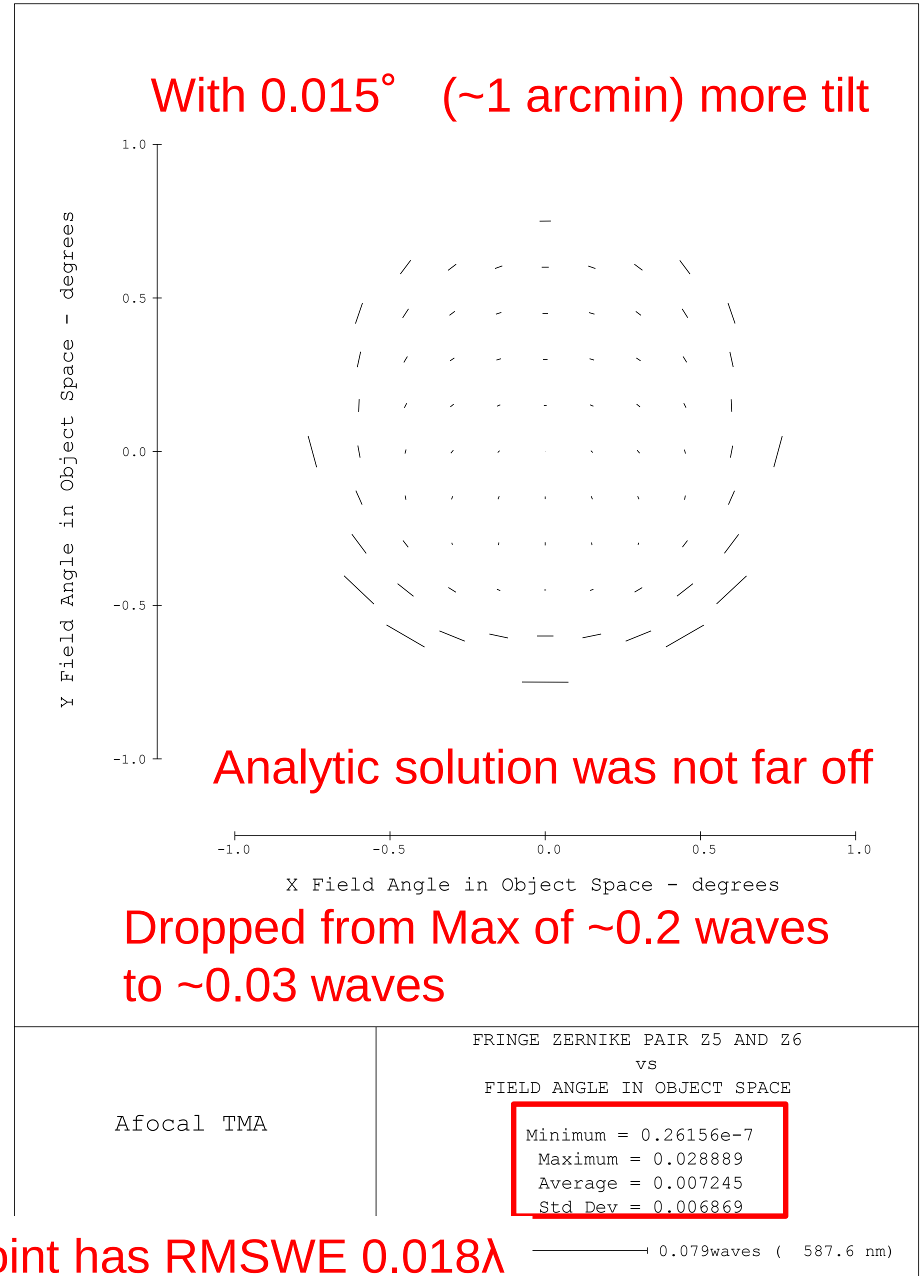
There is some residual field linear field asymmetric astigmatism



Worst field point has RMSWE 0.09λ


10°
-10°
10.015°
150.00 MM
Afocal TMA
JCP 22-Sep-16





Worst field point has RMSWE 0.018λ

Conclusion

- Several analytical starting point design methods are being developed to facilitate a survey of the four-mirror freeform solution space.
- A combination of these methods can allow for unobscured starting points that are corrected for third order image degrading aberrations.

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Questions?