A telescope objective with symmetrically shaped lenses

Author: Jani Achren, jani.achren@incidentangle.fi
Incident Angle Co., Ltd. www.incidentangle.fi
V1.0: 17.03.2017
V1.1: 06.09.2017

Abstract: A symmetrical rapid rectilinear type camera lens is adapted for low-light telescopic use while retaining the symmetry of lens radii for ease of manufacturing. A flat image surface is achieved with a defocus element to compensate for the field curvature.

1. Introduction

Refractive telescopic objectives for low-light imaging, such as used in astronomy and terrestrial viewing, employ established types such as Fraunhofer, Petzval or Cooke for forming an image from infinity to an image plane. For the required spherochromatic aberration correction, the systems generally have 2-4 lenses. Some modern variants have more than four lenses, but are basically derivatives of the above mentioned types.

Camera type configurations are rarely used for low-light imaging due to their small apertures. Increasing the aperture diameter of camera systems introduces too many aberrations for the lenses to correct, and simpy adding lenses to the system creates concerns for both manufacturing cost and weight due to the larger size of the lens.

The following is a description of a four lens rapid rectilinear camera type refractive system modified to meet requirements for low-light observation by increasing the stop diameter without the need to add more lenses for aberration control. Further advantage includes retaining the symmetrical nature of lens shapes from the original rapid rectilinear - the four lens configuration contains only two distinct lens shapes and glass materials.

The main benefits of the described configuration come from manufacturing cost-effectiveness due to the symmetrical surfaces. The quality of the image in the new configuration does not necessarily exceed that of an equivalent Petzval. The lenses described here all have spherical surfaces and use common glasses and thus can be manufactured with traditional techniques. Further benefit can be derived by using high-index low dispersion glasses.

The following description starts with the rapid rectilinear type camera objective, followed by step-by-step introduction and analysis towards low-light application. Design guidelines and requirements for an automated Zemax macro using Global Optimization for designing such objective are also presented, as well as three case studies.

2. Layout

In the following description, light propagates from left (or object space, or from infinite conjugate) towards image space on the right. For the purposes of this description, the stop is located in the middle of the system as it was with the original rapid rectilinear. In finished layouts, moving the stop from the center to the first surface should not dramatically affect the system.

The layout resembles an air separated rapid rectilinear, with lenses oriented in a symmetrical fashion around the stop. Lenses L1 and L2 are positioned in front of stop, or at object space (infinite conjugate) side, whereas lenses L3 and L4 are positioned behind the stop, in reverse orientation to lenses L1 and L2. The stop diameter is slightly smaller than the lens diameters. Radii due to symmetry are as follows:

$$\begin{aligned} R1 &= -R8 \\ R2 &= -R7 \\ R3 &= -R6 \\ R4 &= -R5 \end{aligned} \tag{2.1}$$

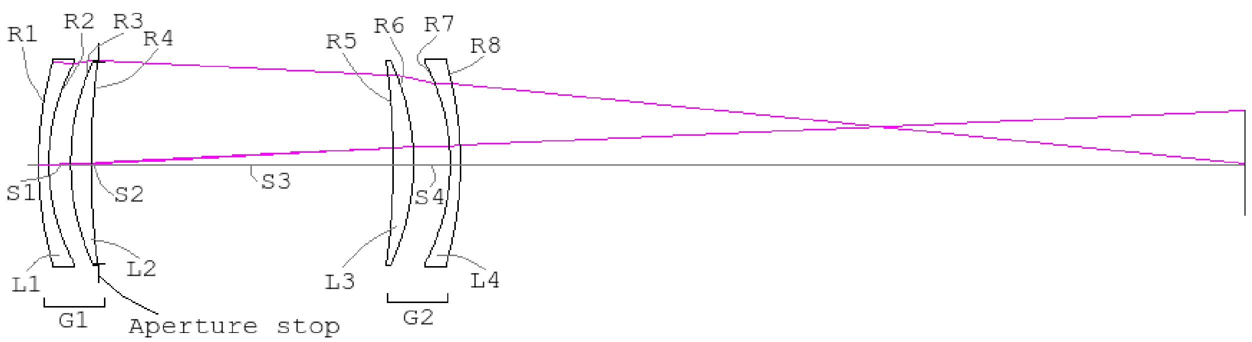


Figure 1: Layout of a f=100 mm system with chief and marginal rays.

First lens L1, a negative power meniscus, has same radii, thickness and glass material as last lens L4. Second lens, a positive power lens L2 is similarly identical to third lens L3. Lenses L1 and L2 form lens group G1, and lenses L3 and L4 form lens group G2.

Symmetry is broken by the separation between the lenses and the stop. Separation S1 between L1 and L2 is smaller than separation S4 between L3 and L4. Separation S2 between L2 and stop is smaller than separation S3 between stop and L3. The stop, located between L2 and L3, is closer to L2 than to L3.

Focal lengths of lens groups G1 and G2 are related to the system focal length according to the following equation:

$$\frac{f_{G2}}{2 f_{system}} < \frac{f_{G1}}{2 f_{system}} < 1 \qquad (2.2)$$

i.e. the focal length of a lens group is approximately twice the system focal length. Focal lengths are offset from each other to create a defocusing element for balancing astigmatism and field curvature for best median image plane.

Glass materials are similarly symmetrical: glass for L1 is the same for L4, and same applies to L2 and L3. Positive power lens glass has a higher Abbe number than the negative power meniscus, but also benefits from high index of refraction.

2.1 Defocusing element

When the focal lengths of G1 and G2 are equal, the field curvature is inwardly curved at the image surface, and astigmatism is nearly corrected. By adjusting the group focal lengths according to (2.2), a negative astigmatism is introduced to the system, while field curvature remains inwardly curved.

Before adjusting the group focal lengths, the order of the field surfaces (from the object side) are Petzval, tangential, medial and sagittal. As image 2A shows, there is very little third-order astigmatism, making the Petzval curvature an accurate description of the image surface.

When negative astigmatism is added by defocusing the lens groups, sagittal and tangential surfaces separate. The tangential surface, which has greater effect on overall aberrations, will bend backwards, towards flat. Sagittal surface bends also backwards, but only slightly.

3. Design and analysis

To demonstrate the design process, the author designed a rapid rectilinear type objective as the starting design. Its first order parameters are a system focal length (f) of 100 mm, full field of view (FFOV) of 50º and a system stop of 1/5 of lens diameters with a relative aperture of F/21.

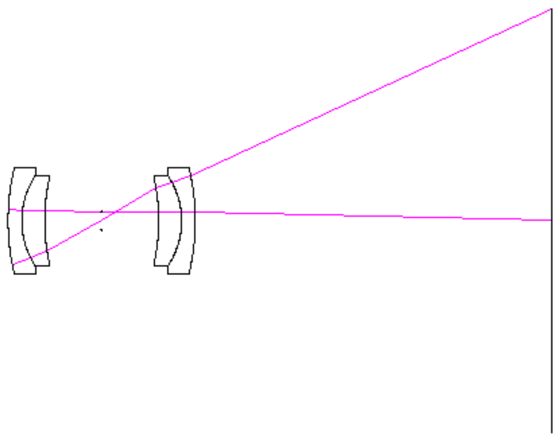


Figure 3: A basic rapid rectilinear camera lens layout.

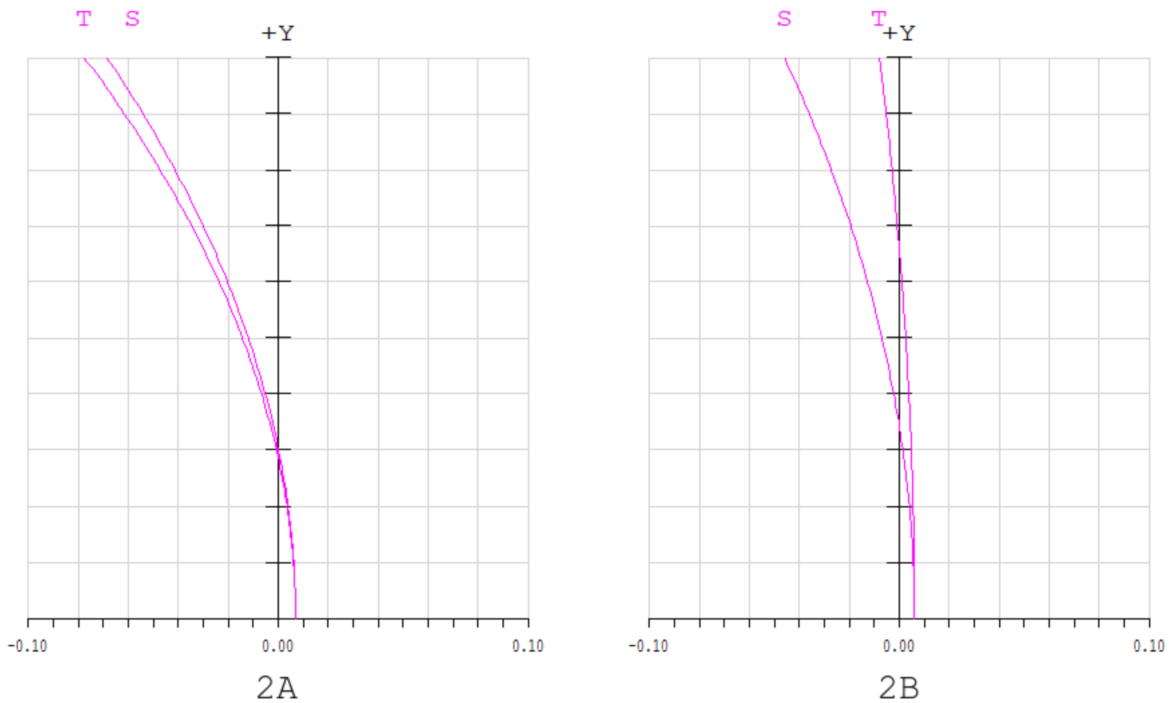


Figure 2: Field curvatures before (2A, left) and after (2B, right) defocusing. Defocusing bends tangential field curvature towards flat.

For the upgrade, the focal length remains the same, whereas FFOV is reduced to 6º, system stop diameter is increased to the scale of the lens diameters, and relative aperture is increased to F/5. Polychromatic RMS spot radius remains comparable in both starting and end designs, approximately half of the diffraction limit throughout the whole respective fields.

3.1 Merit function

Optimization method uses a merit function to determine the quality of the optimization. The basis is the default merit function, which in Zemax controls the transverse aberration in radial direction at the image surface. Because of this, the field points should be assigned geometrically reducing weights. The radii are locked for symmetry with solves. The wavelengths considered were F, d and C of the visible range, with equal weights.

Merit function will have functions for effective focal length as well as working F-number. In addition to (2.2), the merit function should use restrictions on negative distances and in some cases if required, on concave front surfaces of lenses (this is very helpful in reducing formation of ghost flaring). Initially, the contributions from the additional functions to the merit function should be zero.

3.2 Design process

First design step is reducing the FFOV from 50º to 6º, separating the joined lenses and increasing the system aperture. The FFOV does not need to be the final FFOV, but it has to be reasonably low enough for the optimization to be able to correct for the field aberrations. The separations, radii and glass materials of the first lens group G1 are made variable. Radii and glass materials in G2 should follow those of G1 with symmetry solves (2.1).

Abbe number of the postitive power lens should be higher than that of the negative meniscus material. There are several combinations of glasses one can use, including the ones listed below.

	Negative meniscus	Positive lens
Case 1	501567	434950
Case 2	558540	487845
Case 3	571530	439949

Table 1: Glass materials for three cases. Glass is indicated by a six-digit glass code.

During the first optimization run, separation S3 should be tied to S2 and S4 to S1 with solves. This would optimize the system for axial aberrations while retaining a perfect symmetry around the stop. The center is corrected, but field is curved inwards. Field curvature is positive and

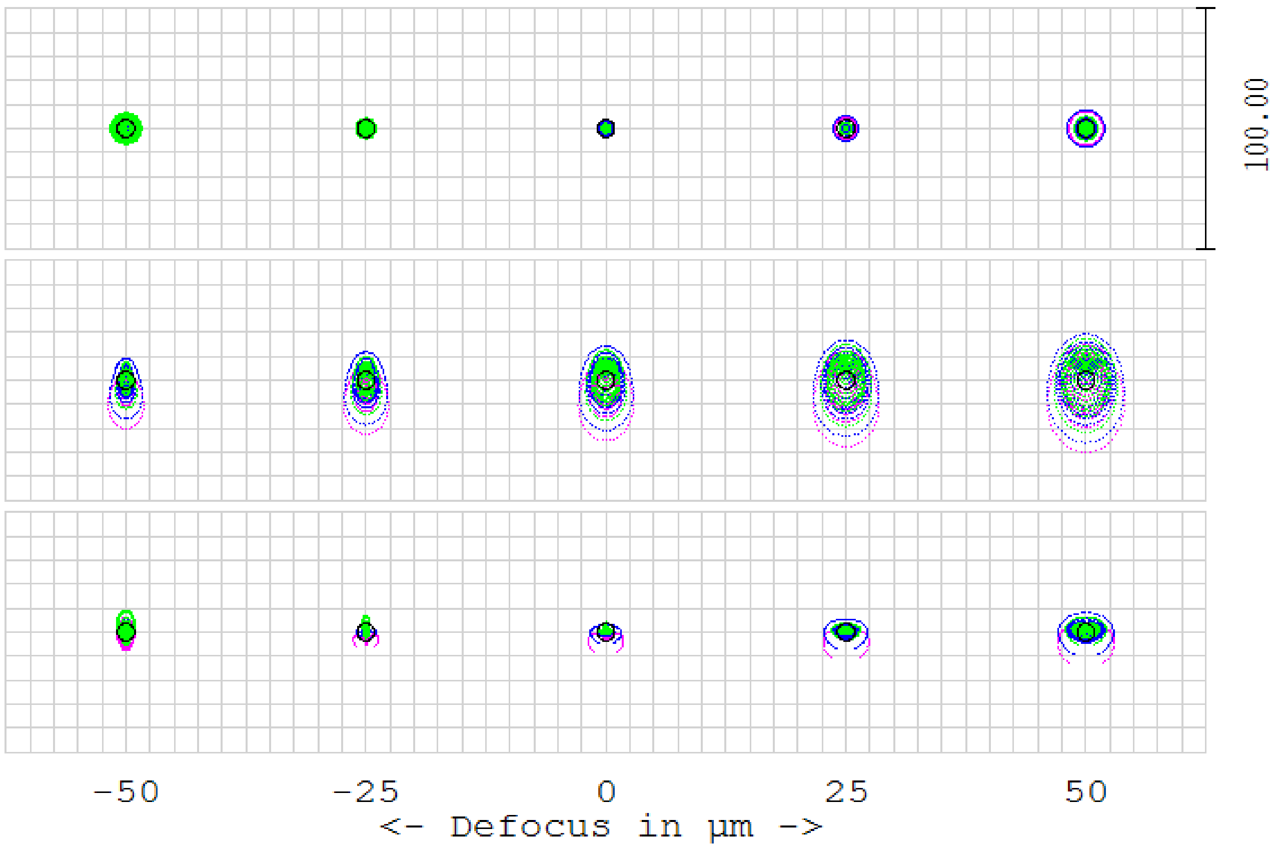


Figure 4: Spot diagrams through focus for axial image (top), and edge image (FFOV 6º) where lens group focal lengths are equal (middle), and where lens group focal lengths differ by a factor of 0.944 (bottom). The term defocus in the graph refers to image plane defocus, not the lens group defocus used in this paper.

third-order astigmatism is close to zero.

When S3 and S4 are made variable and the optimization run again, astigmatism increases in value and is negative, while field curvature remains positive. The tangential curvature separates from sagittal curvature and bends toward flat like in figure 2.

The variation of S1 from S4 and S2 from S3 forces the lens groups to defocus from each other, but not by much. Figure 4 demonstrates the spot diagrams through focus for the center axis and edge in two cases, one where lens group focal lengths are equal and one where they differ by a factor of 0.944.

3.3 Alternate approach to design

For larger aperture objectives, author used a template with four slab plates of Schott N-BK7 glass with initial 1 mm separations and convenient thickness, a system stop at the middle and an aperture diameter equal to the slabs, and above mentioned merit functions in addition to the default merit function. Radii of the first two slabs and all separations were set as variables with merit functions to keep them positive. Radii of the last two slabs were fixed with solves to the first two slabs as per (2.1). A moderate field angle of 4º was set with a middle point at 0.7r. Focal length was set within merit function to a reasonable range, which is F/5 or slower. Faster systems are possible with a high Abbe, high index glasses for the positivel lens. Additional control of system aperture is possible with a working F-number merit function. Glasses are set as substitute solves with chosen glass catalogs.

With the above settings, a Global Optimization should converge to a convenient starting point in short time, after which the correct field angles can be adjusted, along with any radii solves that can be released.

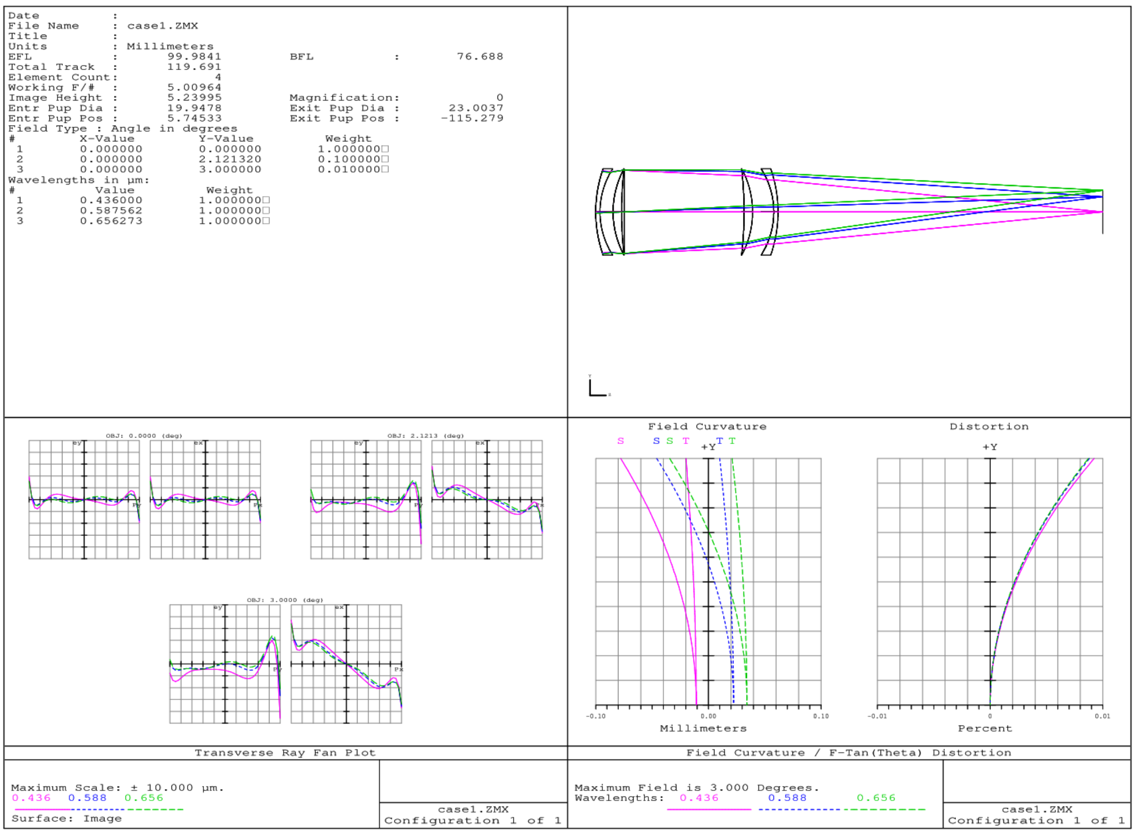
4. Conclusions

I have described a four lens refractive objective derived from a rapid rectilinear type camera lens. The derived objective retained the element symmetry from the original type to reduce manufacturing costs, and an enlargened system stop to enable stronger light-gathering power for low-light use. The original field of view was reduced, resulting in better air glow penetration for astronomical applications. The resulting objective has comparative imaging performance to modern Petzval type objectives, with less manufacturing involved.

An automated process suitable for a Zemax macro has been described. Author has used the described automated process to design a dozen designs of apertures between 80 mm and 160 mm, and with relative apertures as fast as F/5.5 with minimal user input and interference, with image sizes appropriate for both Full Frame and Medium format sensors.

5. Discussion

Symmetrical four lens configuration is a good starting point for more complex designs. Lenses can be split and added, and the symmetry of the radii can be relaxed at the expense of increasing manufacturing costs, but with increased imaging quality. For using aspherical surfaces, the suitability of a reversed aspherical surface to the system must be verified in each case. The positive power lens benefits greatly from high Abbe number and high index of refraction.

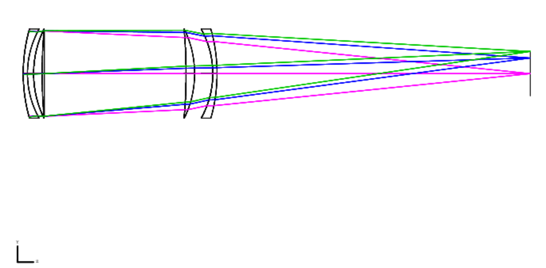


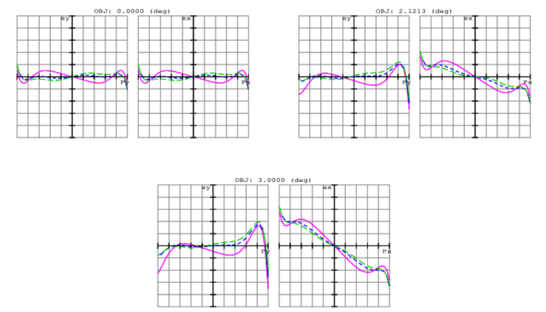
Date :
File Name : case2.ZMX
Title :
Units : Millimeters
EFL : 99.9833 BFL : 73.7418
Total Track : 119.325
Element Count: 4
Working F/# : 4.95581
Image Height : 5.2399 Magnification: 0
Entr Pup Dia : 20.1693 Exit Pup Dia : 23.959
Entr Pup Pos : 3.97997 Exit Pup Pos : -118.754
Field Type : Angle in degrees

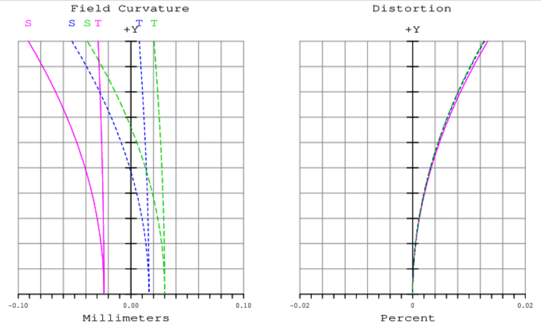
#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	2.121320	0.100000
3	0.000000	3.000000	0.010000

Wavelengths in µm:

#	Value	Weight
1	0.436000	1.000000
2	0.587562	1.000000
3	0.656273	1.000000







Transverse Ray Fan Plot

Field Curvature / F-Tan(Theta) Distortion

Maximum Scale: ± 10.000 µm.
0.436 0.588 0.656
Surface: Image

case2.ZMX
Configuration 1 of 1

Maximum Field is 3.000 Degrees.
Wavelengths: 0.436 0.588 0.656

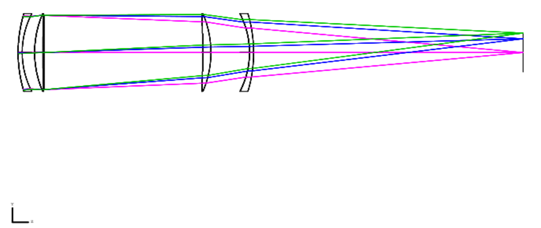
case2.ZMX
Configuration 1 of 1

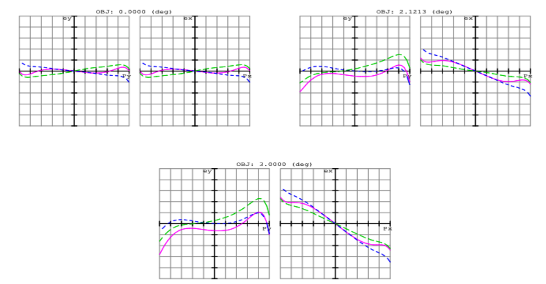
Date :
File Name : case3.ZMX
Title :
Units : Millimeters
EFL : 99.9647 BFL : 65.742
Total Track : 123.202
Element Count: 4
Working F/# : 5.03092
Image Height : 5.23893 Magnification: 0
Entr Pup Dia : 19.8689 Exit Pup Dia : 23.8309
Entr Pup Pos : 5.28377 Exit Pup Pos : -119.907
Field Type : Angle in degrees

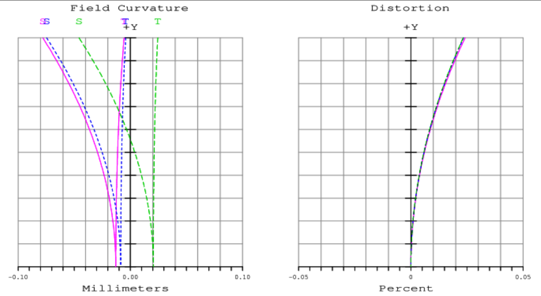
#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	2.121320	0.100000
3	0.000000	3.000000	0.010000

Wavelengths in µm:

#	Value	Weight
1	0.436000	1.000000
2	0.587562	1.000000
3	0.656273	1.000000







Transverse Ray Fan Plot

Field Curvature / F-Tan(Theta) Distortion

Maximum Scale: ± 10.000 µm.
0.436 0.588 0.656
Surface: Image

case3.ZMX
Configuration 1 of 1

Maximum Field is 3.000 Degrees.
Wavelengths: 0.436 0.588 0.656

case3.ZMX
Configuration 1 of 1