Optical Aberrations 1.2

Prepared
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Introduction

A lens does not focus light perfectly throughout its entire image field. The destination error of ray displays a dependency upon its location within the pupil of the lens. These destination errors are described by *Seidel aberrations*[1]. There are 5 types of Seidel aberrations: *spherical aberration*, *coma*, *astigmatism*, *field curvature*, and *distortion*. There are also two chromatic aberrations: *axial color*, and lateral *color*.

A *ray intercept plot* displays the polynomial dependencies of destination error upon pupil position of rays within the imaging system. A *third-order system* displays ray intercept curves which are dominated by polynomials of third order or less, while a *fifth-order system* displays ray intercept plot which is dominated by fifth-order polynomials. Typically, a fifth-order system is more complex than a third-order system.

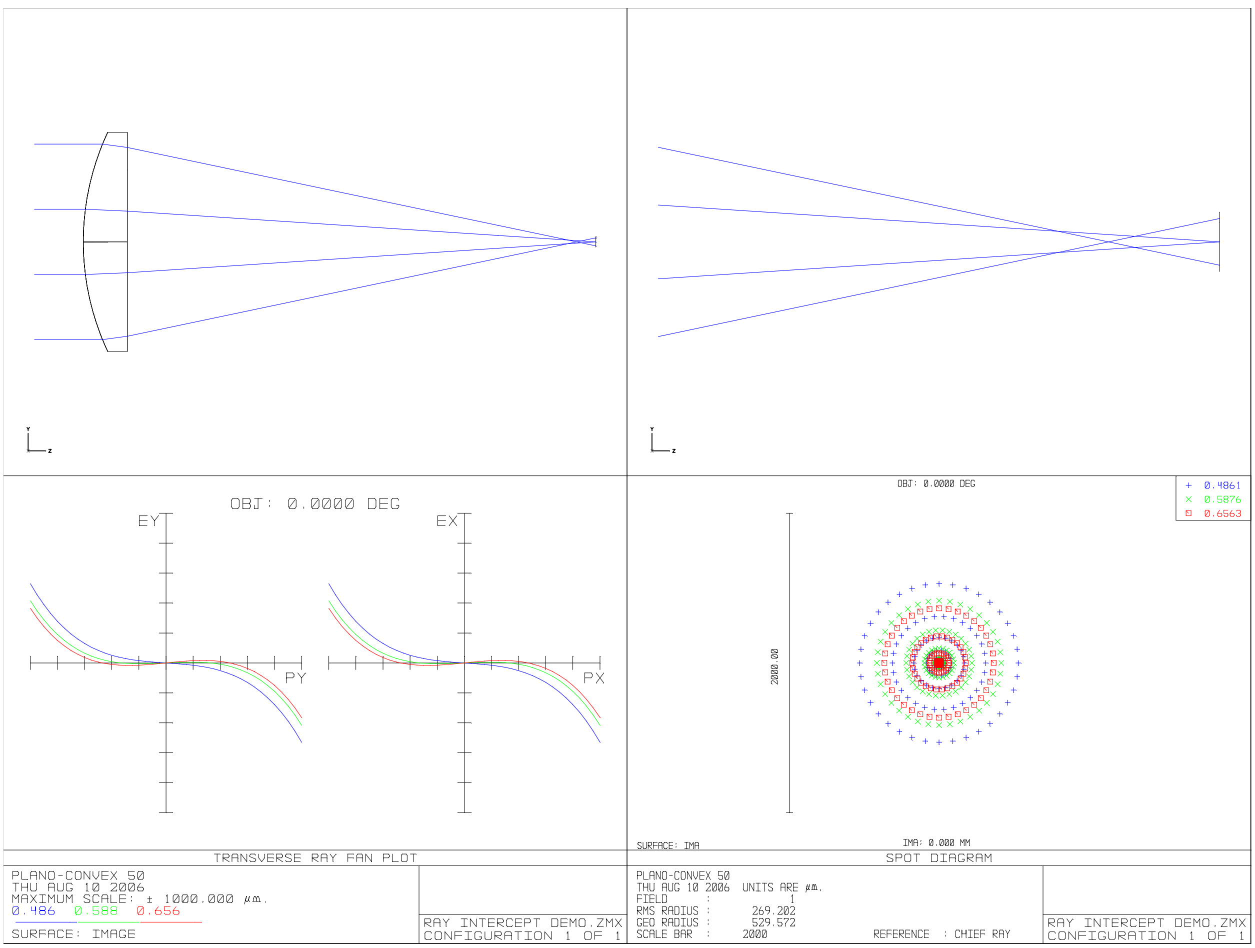

Figure 1 Ray-intercept plot of plano-convex lens with 50mm folcal length

[1] W.J. Smith, *Modern Optical Engineering*, 2nd ed. New York: McGraw-Hill, 1990.

Seidel aberrations specify the destination error of a ray through a linear summation of parameters to powers 1 though 5. A 3rd model of aberration addresses powers up to 3 which is cubic polynomial. A 5th order model is frequently employed with computation methods. Each Seidel aberration is associated with particular polynomial. Spherical aberration is associated with a cubic ray intercept plot, while coma is associated with a parabola. Identification of aberrations can indicate particular changes to the design of an optical system.

There are three types of degrees-of-freedom within a lens design: surface topography, thickness of material, and type of material. A minimum of one degree-of-freedom within a lens design is required for control each aberration.

All lenses within this document are 50mm in focal length.

Spherical aberration

The spherical lens of Figure 2 displays a cubic ray-intercept plot, whereas a perfect lens would display a flat line at steady ordinate of zero. The margin of a spherical surface bends light too much. Consequently the margin rays are focused before central rays as seem in upper right quadrant. PY and PX are the positions of the ray within the entrance pupil at left, while EY and EX are the errors in position of the rays at termination plane. A cubic ray-intercept plot indicates spherical aberration.

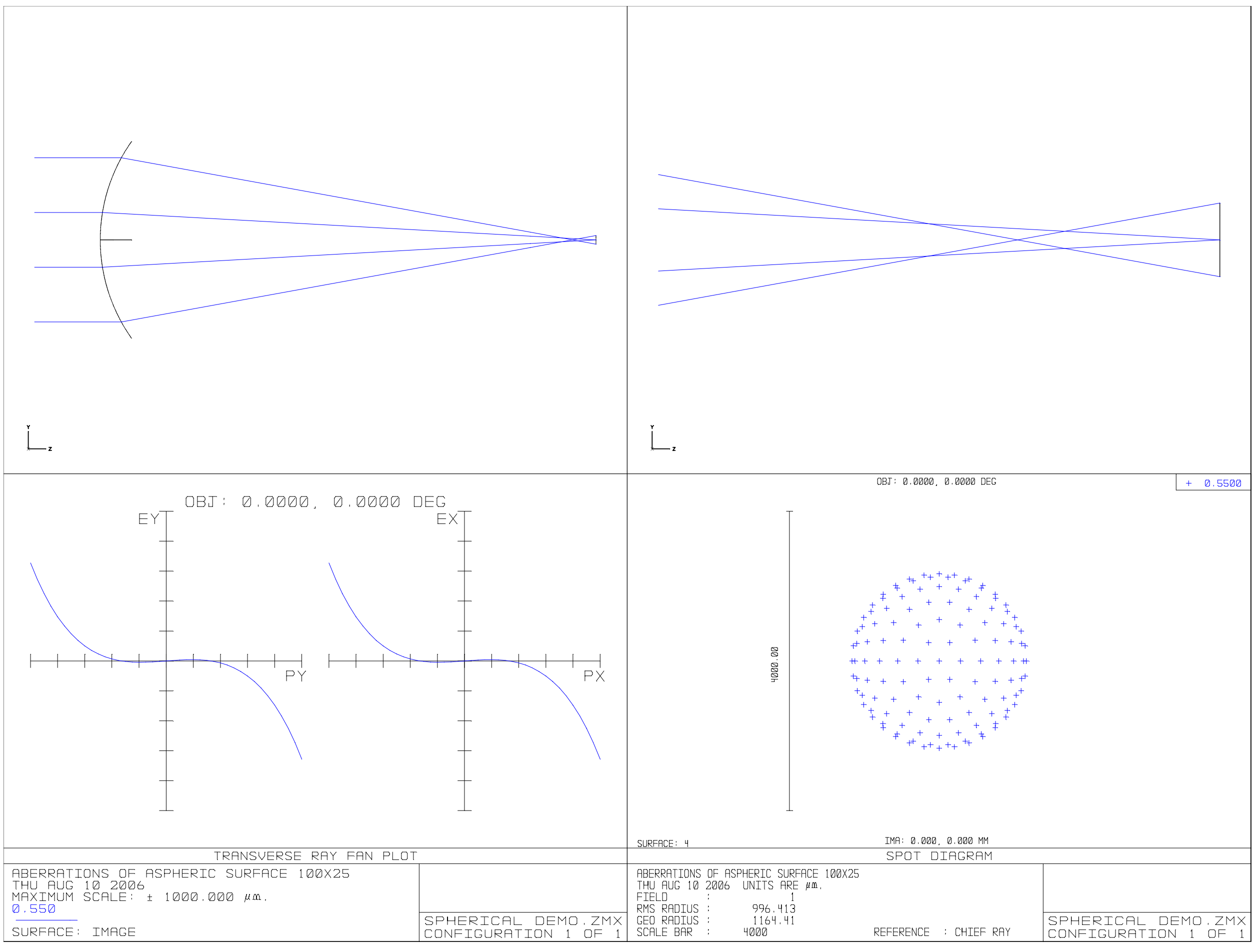

Figure 2 Cubic polynomial of spherical aberration.

Sharp focus

An aspheric surface reduces refraction at the margins. An ellipse provides the perfect form for this on-axis image. The margins of the ellipse are less sloped than a sphere. Figure 3 displays perfect focus of the on-axis rays. The ray-intercept is a flat line of zero which indicates perfect focus.

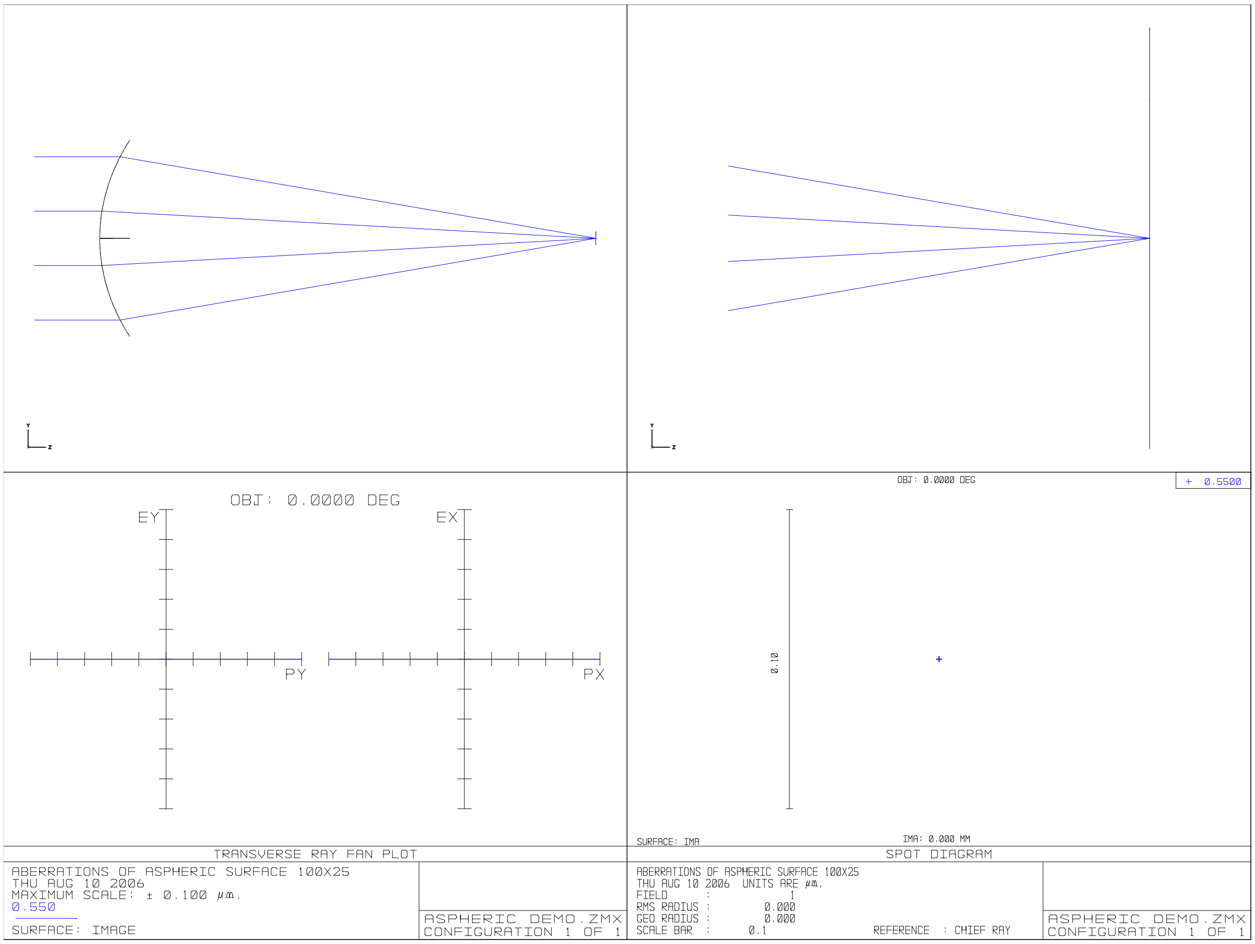

Figure 3 Flat line of aspheric lens with perfect focus

Coma

A focused spot within the off-axis field frequently displays a fuzzy tail which resembles a comet. This off-axis aberration is called coma after the Greek word for hair *komē*. A comet is actually a hairy star or *komētēs* or *komē astēr*. Coma is also due to spherical shape of the lens, but it only occurs at off-axis points within the image; it does not appear on-axis. Coma displays a parabolic ray-intercept plot.

The aspheric lens of Figure 4 displays a parabolic ray-intercept plot in the off-axis field. A parabolic ray-intercept plot indicates coma. Coma is found only in off-axis fields. As the field angle increases, the margin of the lens shifts downward and backward. Consequently, marginal focus is also shifted downward and backwards as seen in the upper quadrant. The aberration coma creates a spot pattern resembling a comet.

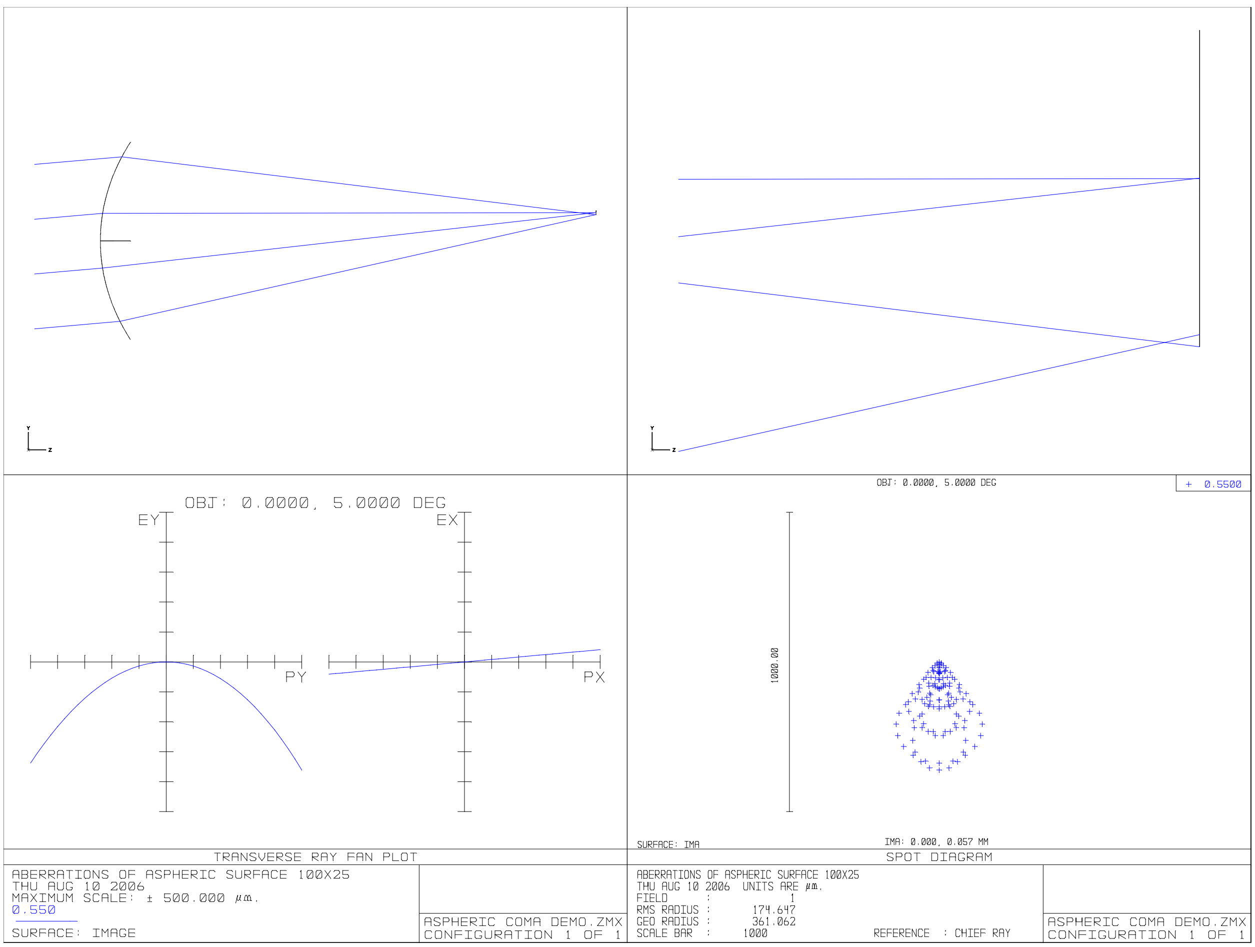

Figure 4 Parabolic polynomial of coma in off-axis field.

Axial color

The aspheric lens of Figure 5 displays a linear ray-intercept plot of axial color. The flat linear slope of blue indicates sharp focus, while the sloped green ray-intercept indicates defocus. The blue light focuses before the green light due to the refractive index difference between the wavelengths.

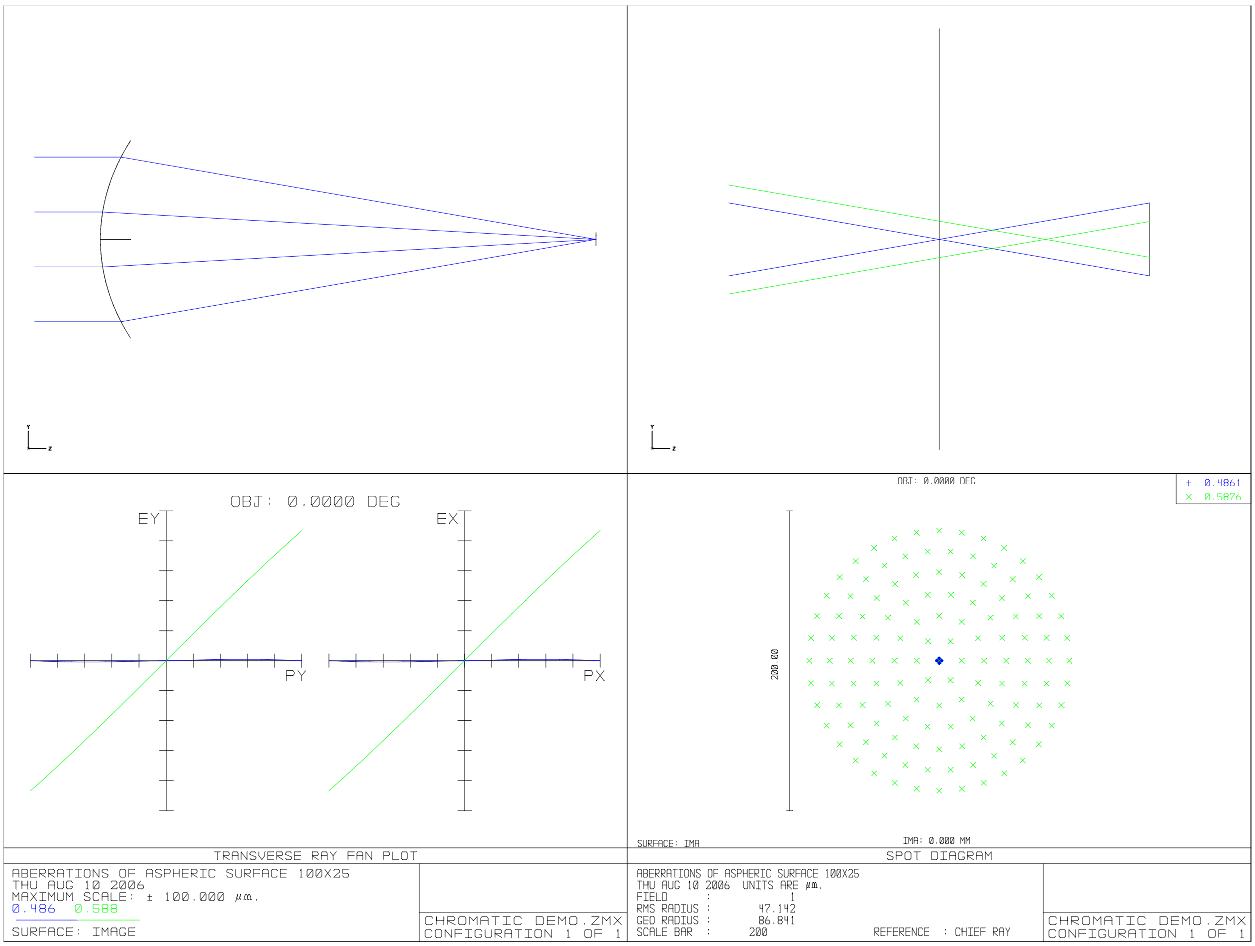

Figure 5 Linear slope of axial color within aspheric lens.

Lateral color

Lateral displays vertical shift between ray-intercept plots of different wave lengths. A wedge within the margin creates lateral color as display in Figure 6. An on-axis ray bundle would display no later color.

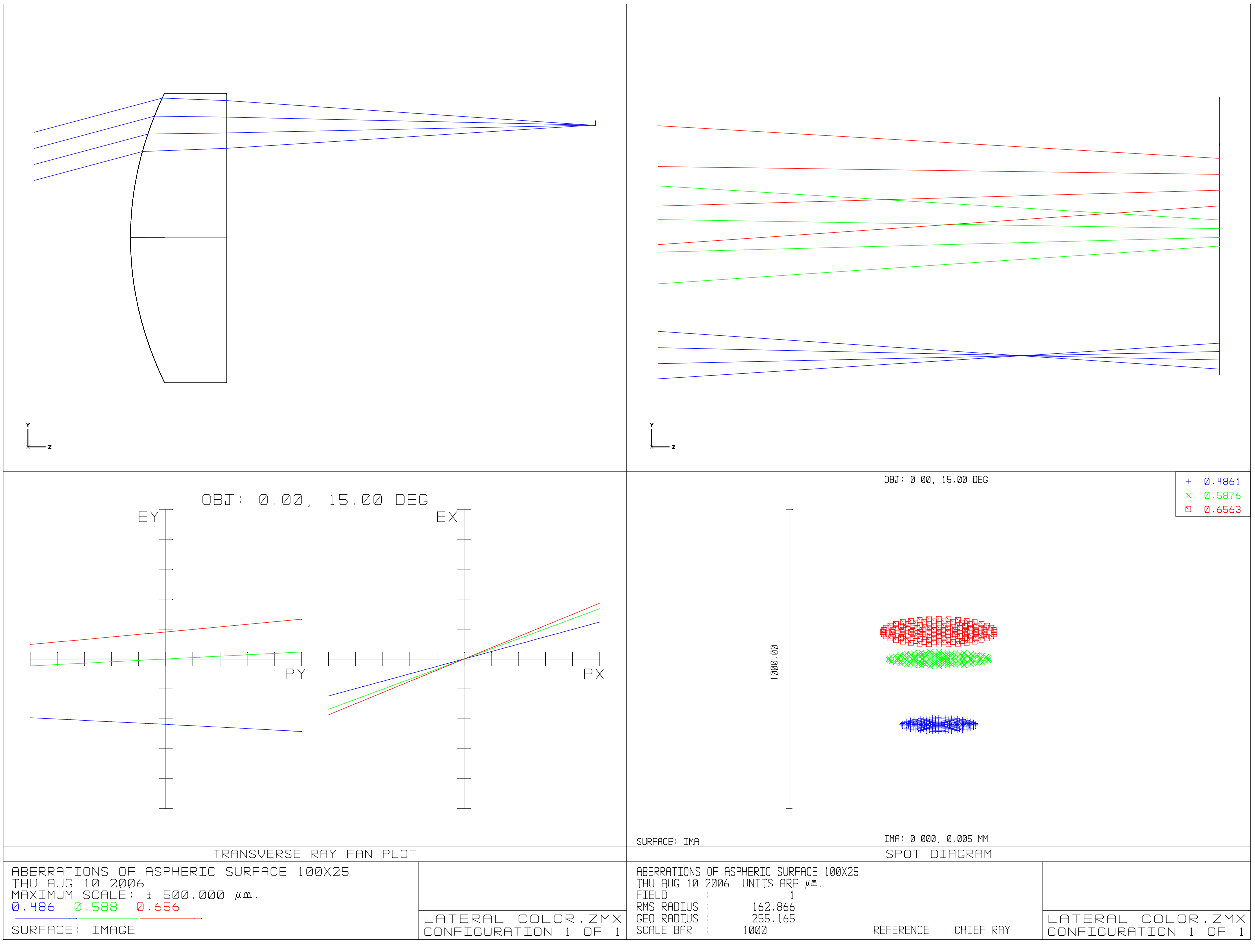

Figure 6 Shifted focal lines of lateral color

Aberrations of plate within convergent beam

A plate within a convergent ray-fan creates both spherical aberration and coma as displayed in Figure 7. The marginal rays focus beyond the central rays. Consequently, the ray-intercept has the opposite polarity to the spherical lens. A plate should be placed within only collimated rays unless the lens is corrected for such a plate. The coma exceeds 100µm which is much larger than a CCD element of 10µm.

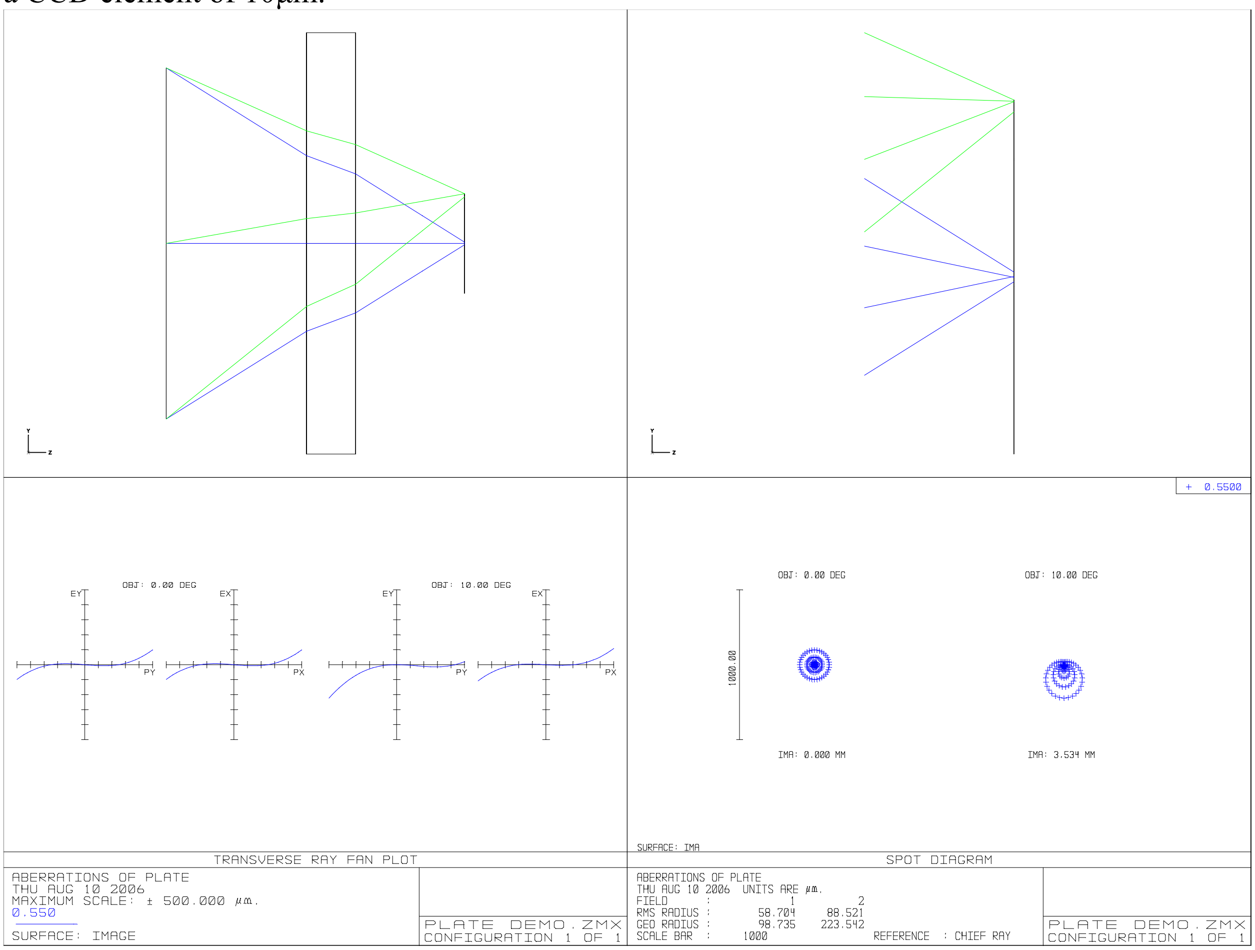

Figure 7 Aberrations of plate within convergent ray-fan

At a small convergence, the aberrations of a plate may become may become acceptable as seen in Figure 8. Only 3µm of coma is likely acceptable for a CCD element of 10µm.

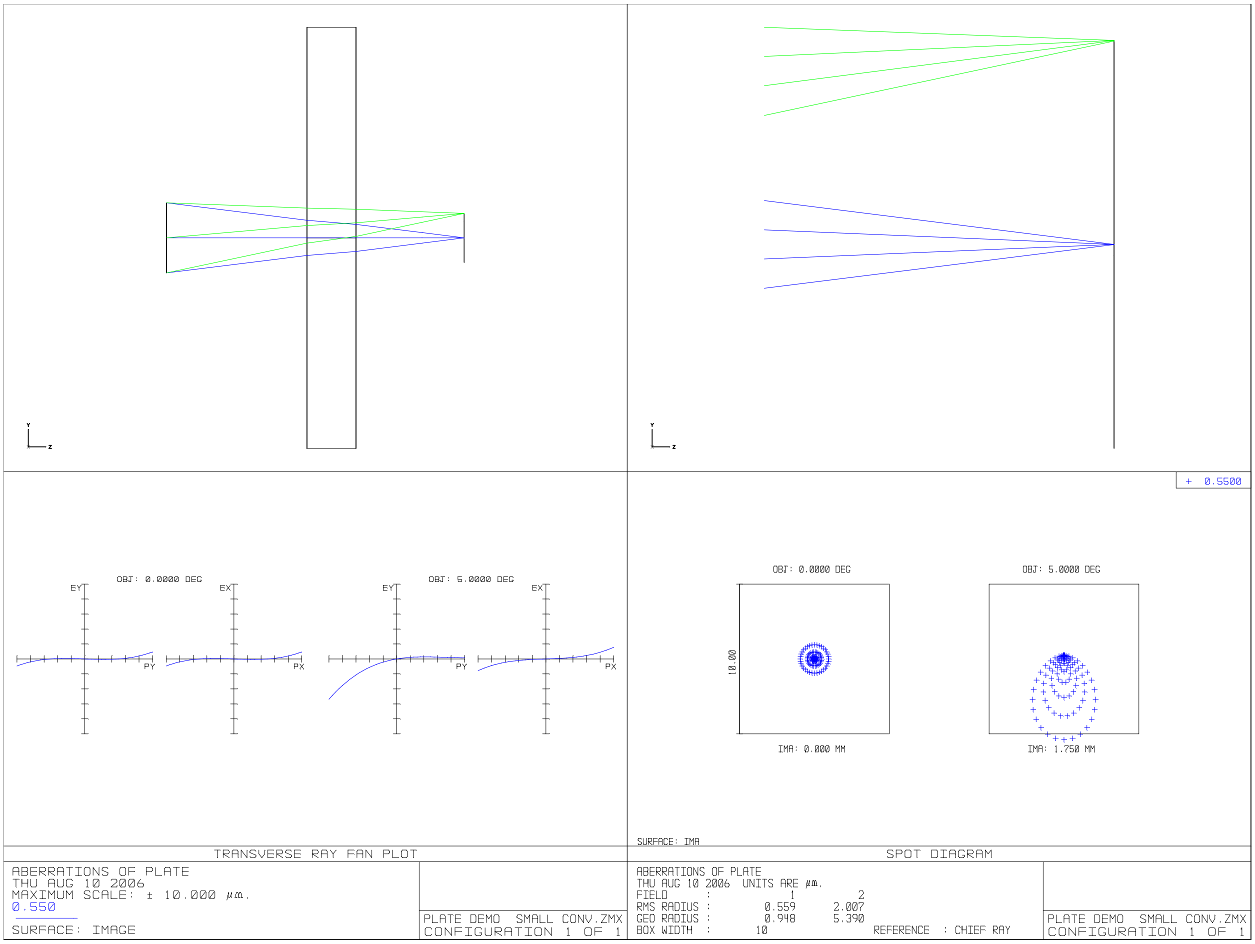

Figure 8 Aberrations of plate within small convergent ray-fan

Astigmatism of tilted plate

Addition of tilt to the plate creates a huge amount of astigmatism as seen in Figure 6 where the rays do focus within the plane of tilt. The 200µm of astigmatism far exceeds a CCD element of 10µm. Tilt of any element, even a lens, creates astigmatism.

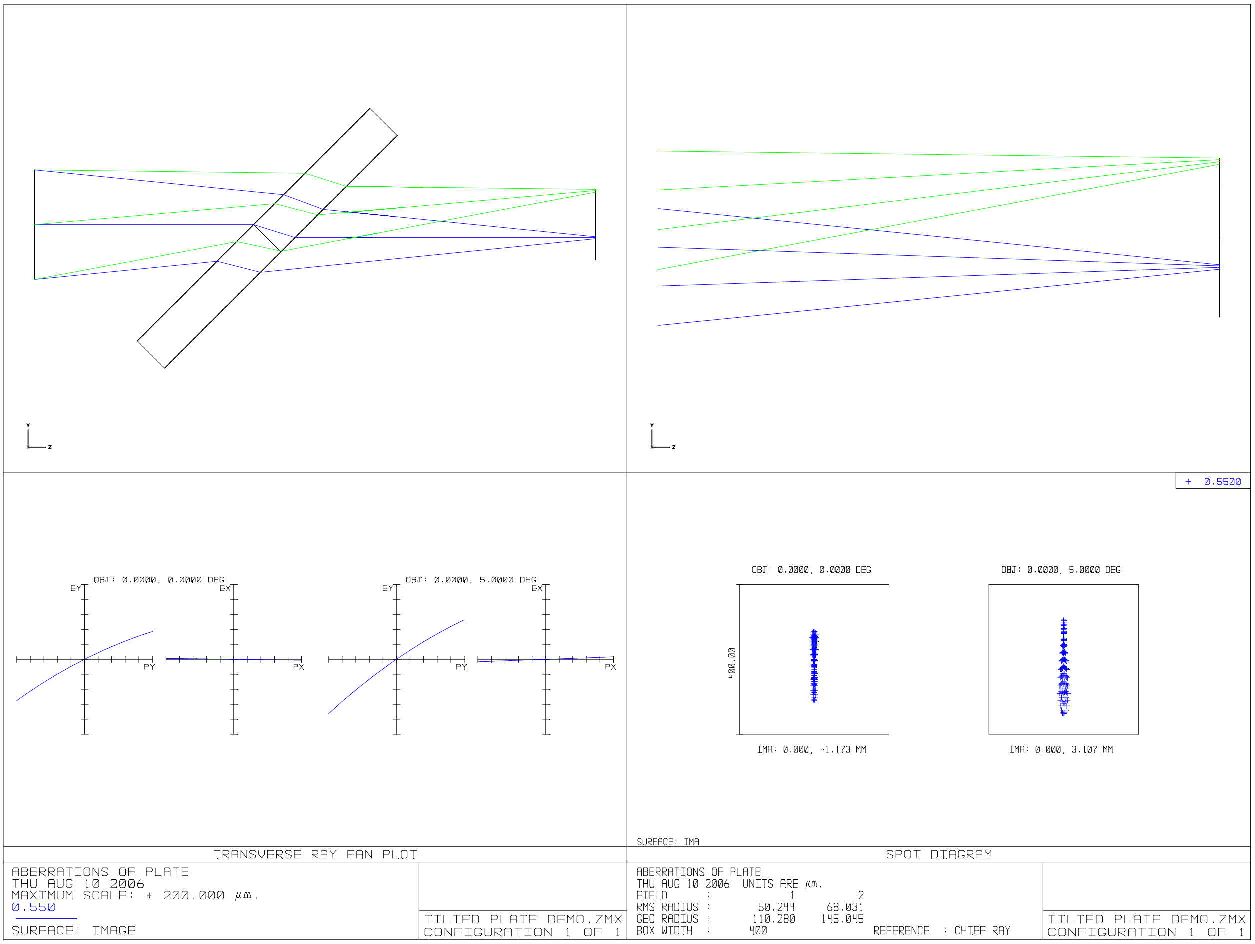

Figure 6 Aberrations of tilted plate within small convergent ray-fan

Field curvature

Field curvature displays a change in slope between ray-intercepts of different fields as seen in Figure 9.

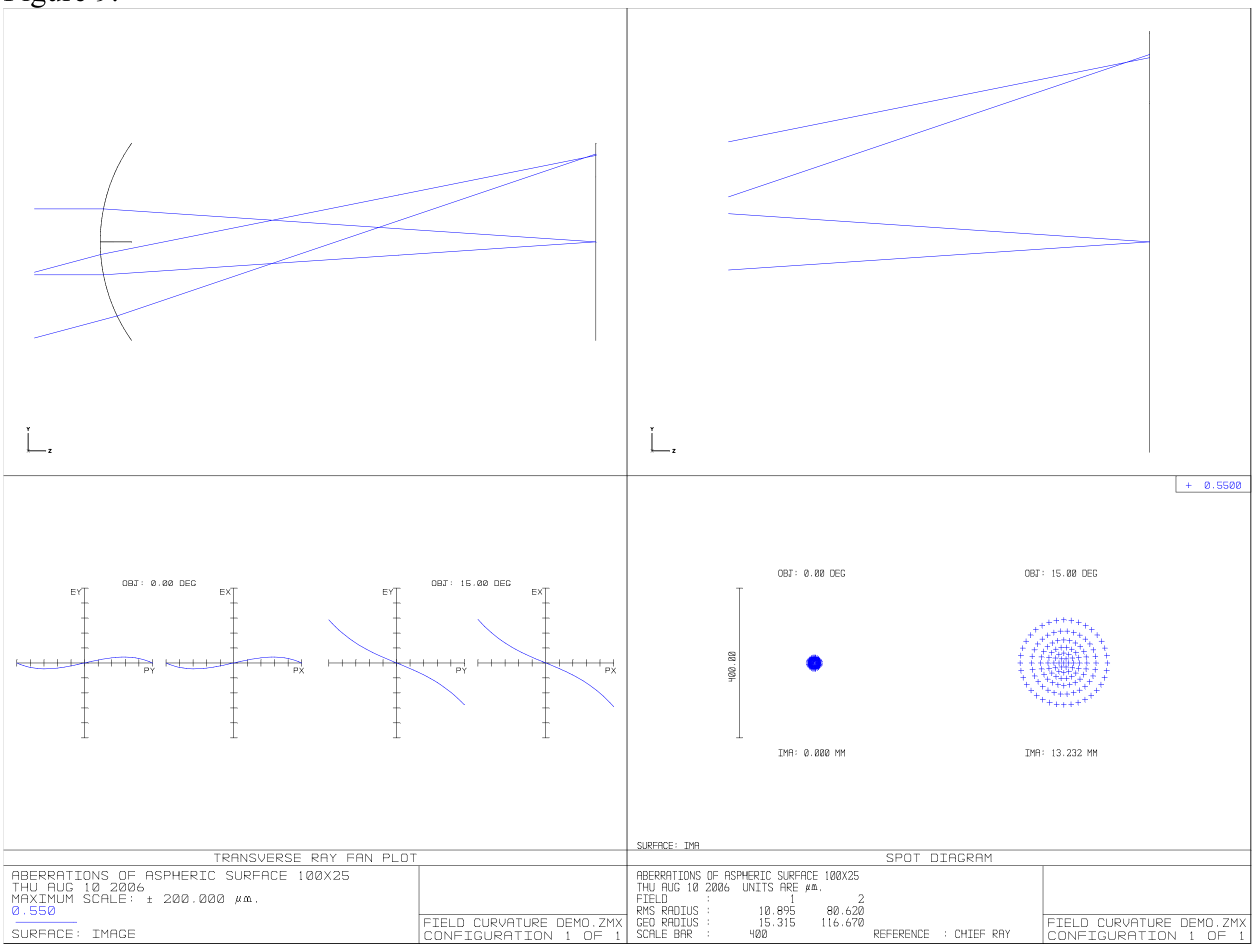

Figure 9 Groth of linear slope with defocus of field curvature

Distortion

Distortion becomes prominent in large angular fields. Consequently, the image magnification may grow with field angle to create a *pincushion distortion*; or the magnification decrease to field angle to create a *barrel distortion*. Addition of second spherical surface field curvature demo lens may eliminate the field curvature to expand the angular field. The meniscus lens in Figure 10 displays a 30º field without defocus of field curvature. However, there is a 10% pincushion distortion as displayed in Figure 11.

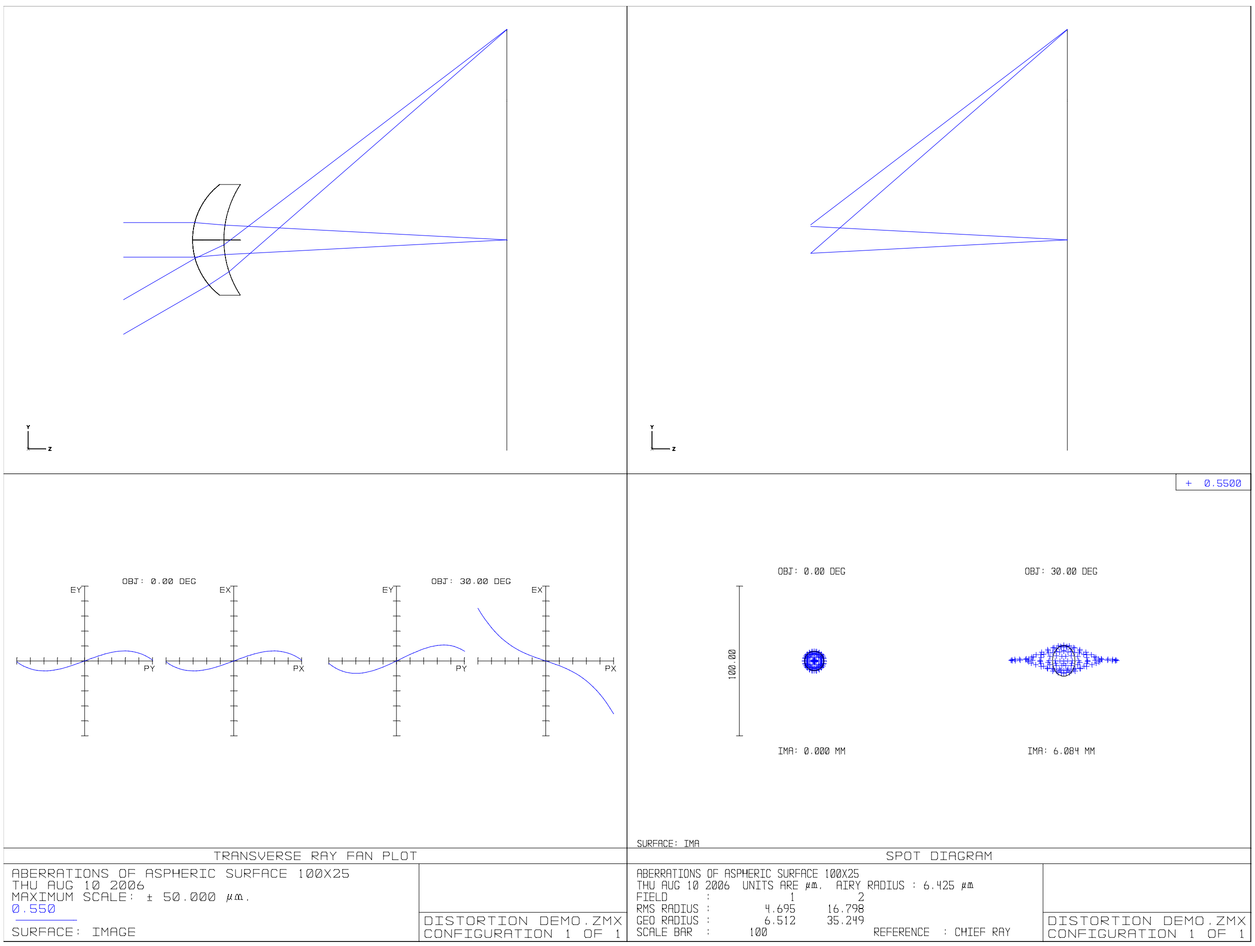

Figure 10 Flat field of large-field menisucus lens

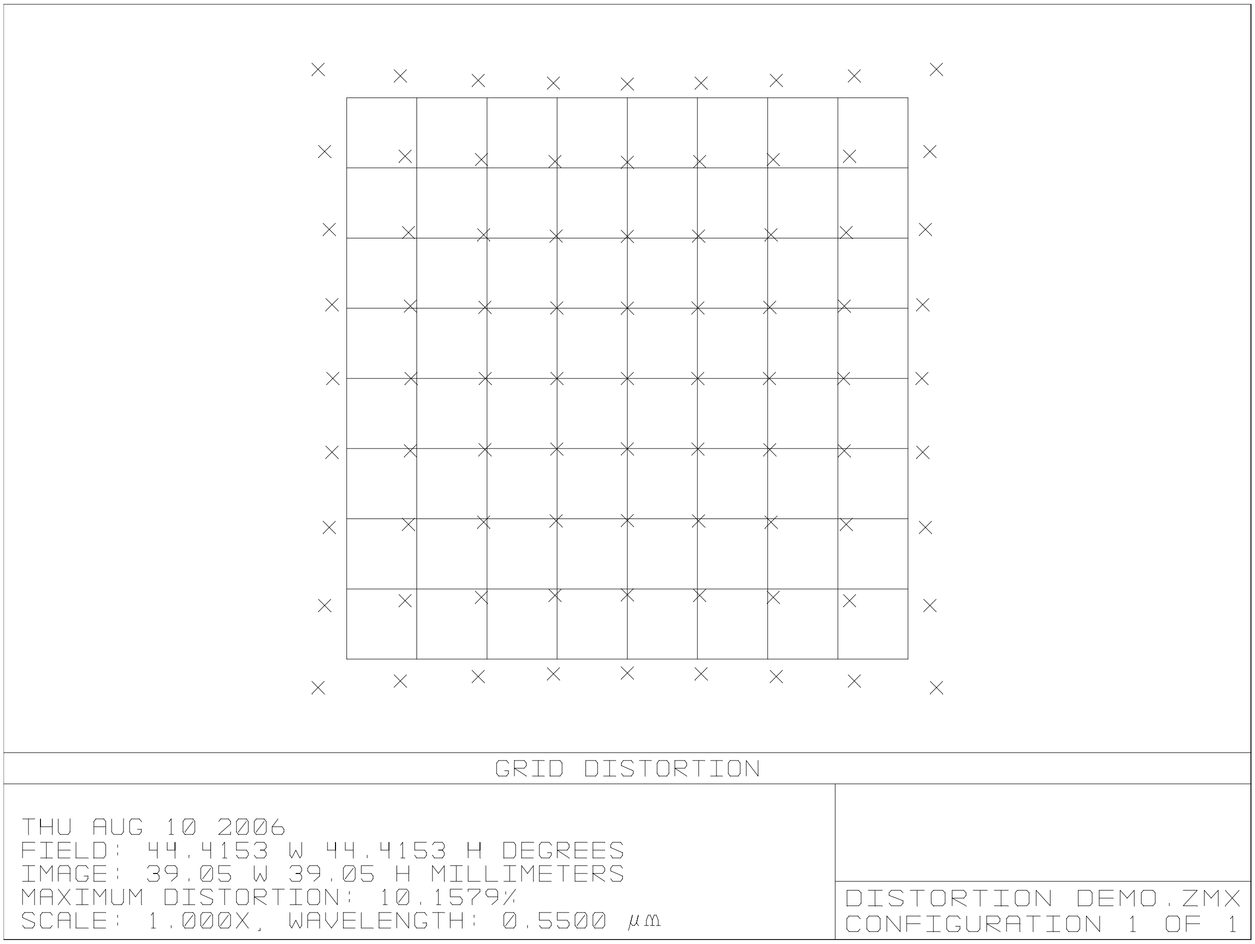

Figure 11 Pincushion distrotion of large-field menicus lens.