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Improvement on f/# of Optical Entities by Means of Polynomial Aspheric Surfaces

The aperture of traditional apochromatic triplets is limited to f/10…f/8. There are very few methods to increase it. The paper presents a computer – aided one. The last surface of the spherically – surfaced triplet is turned into a conic - generated one, using the interactive optimization module of software OSLO LT. The aspheric solution assures double aperture (up to f/5) and high image quality (diffraction-limited system).

Keywords: *apochromatic triplet, f - number, aspheric surfaces, diffraction limited*

1. Introduction

The aspheric surfaces are expensive to machine but are well-known as the most efficient solution to correct spherical aberration. An aspheric surface can significantly improve the image quality, as a general rule but it can increase the aperture, as a special trait.

Large amounts of residual spherical aberration and, consequently, small apertures are specific to cemented triplets. This is why the authors thought of introducing an aspheric surface instead a spherical one.

2. Numerical modeling

Considering a classic design method for a cemented triplet, [1], with the input data: f′=100, s= - ∞, $\omega=5^{\circ}$, and a glass choice FK54-LAK33-TIF6 (Schott sorts), the solution is diffraction-limited (RMS OPD <0.07λ and Strehl ratio>0.80) up to the aperture of f/6.25 (fig. 1).

A small increasing of the aperture produces a fast loss of quality. For instance at h=5 mm (f/10) the Strehl ratio is 0.967. At h=10 mm (f/5) the Strehl ratio becomes 0.209 (fig. 2), which is unacceptable. This large decrease is due to a fast increasing of longitudinal spherical aberration, which is strongly nonlinear linked to height (the aberration is approximately proportional to the square of the height).

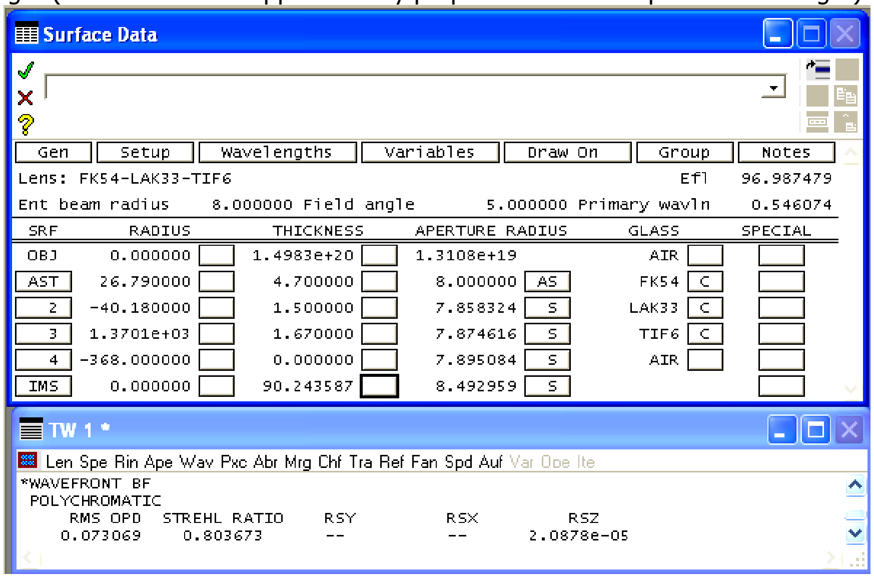

Figure 1. Surface data and wavefront parameters at aperture f/6.25

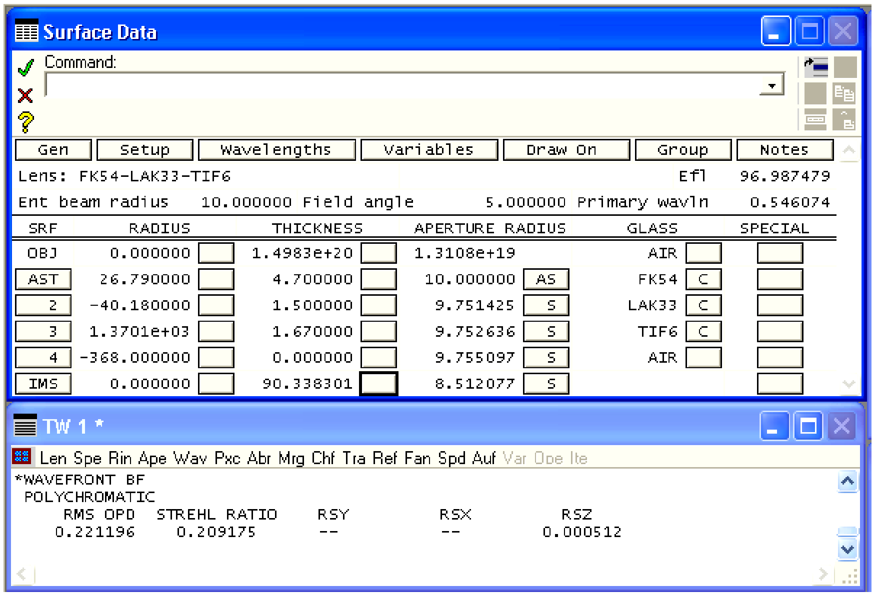

Figure 2. Surface data and wavefront parameters at aperture f/5

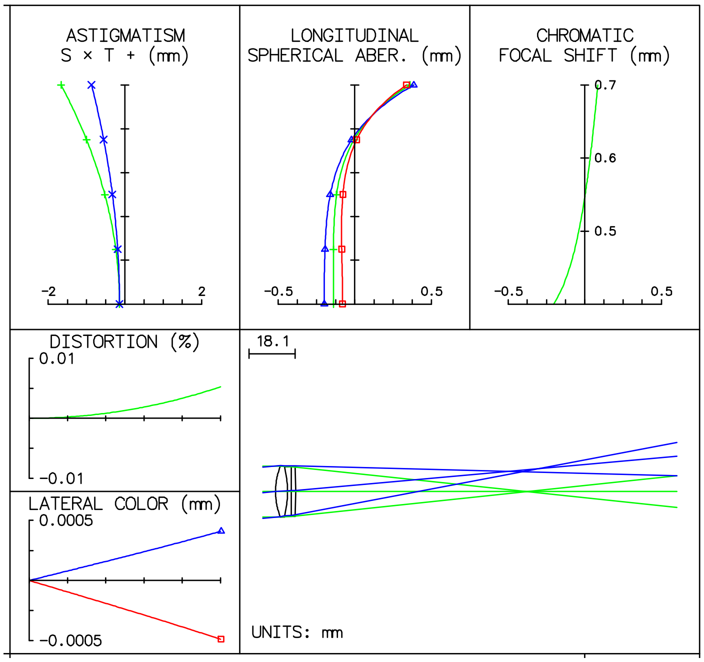

Figure 3. Spherochromatism and chromatic focal shift at a double aperture (f/5)

Indeed, as figure 3 shows, the longitudinal spherical aberration gets a very high gradient in respect with height. The spherochromatism indicates that the apochromatism is preserved as well as the focal chromatic shift. That means the chromatic characteristics are independent to incidence height and the vulnerable element resides in spherical residual aberration. Figure 4 details the spherochromatism and the chromatic focal shift.

Bending is not efficient in changing the shape of spherochromatism curves. Small changes of radii or thicknesses actually introduce only smaller or larger amounts of defocusing but have no effect on curves' shape.

The only possibility to change the spherochromatic curves' shape is to turn one of the spherical surfaces into an aspheric one. The authors propose this transformation for the last surface (the fourth one).

It is useful a special module of software OSLO LT from the Sinclair Optics Company. This optimization module allows the operator to indicate the parameter to modify and to introduce the value manually. The program is built with intelligent interactive facilities, which allow the human operator to decide the interpretation of the results and to appreciate their values. The interactive operations use a special window called "Slider wheel" (fig. 5).

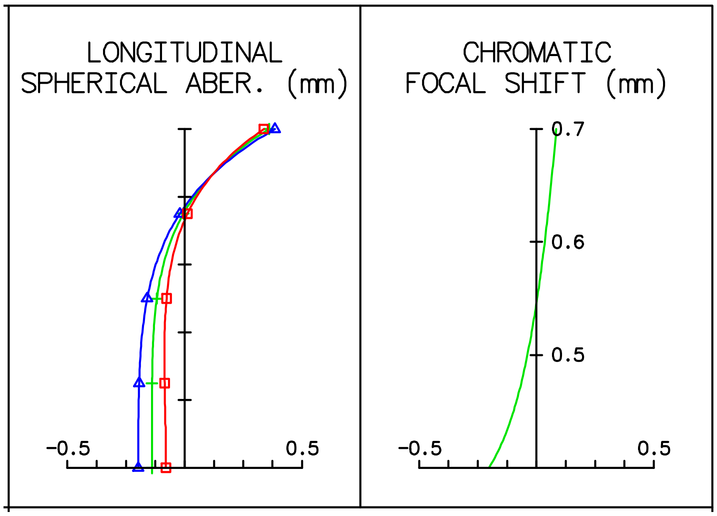

Figure 4. Spherochromatism and chromatic shift are not affected by increasing aperture

The slider-wheel setup defines the variable parameters. Beside the conic constant (CC4) of the forth surface, the authors introduced a second variable, the thickness of the middle lens (TH2). Different values of CC modify the shape of the residual spherical aberration, while TH2 controls the position of the spherochromatic curves along the optical axis.

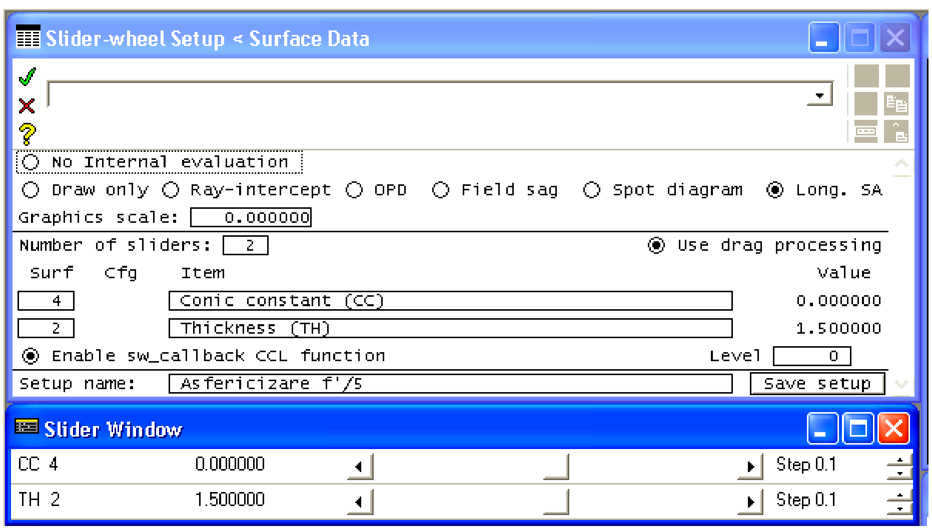

Figure 5. Slider wheel window

Figure 6 shows the final modified shape of the spherochromatic curves and the slider window containing the proper values of both conical constant (CC4) and thickness (TH2).

The last surface became a part of an ellipsoid whose constant is 89 and the thickness of the central lens became 2.1 (fig. 6).

The effect of replacing the last spherical surface with an aspheric one is equivalent to turning a week quality system into a diffraction-limited one (fig. 7) at an f-number equal to f/5, which means, practically, a double aperture.

Figure 8 shows the residual geometrical and chromatic aberrations of the aspheric system. Their shape and maximum values confirm the high image quality and the preservation of chromatic characteristics specific to triplets (axial chromatic and secondary spectrum).

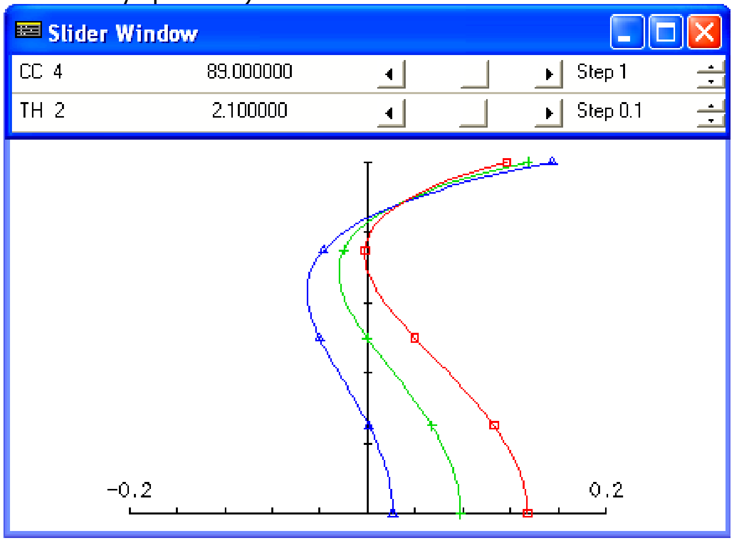

Figure 6. Final shape of spherochromatic curves and their axial position along the optical axis

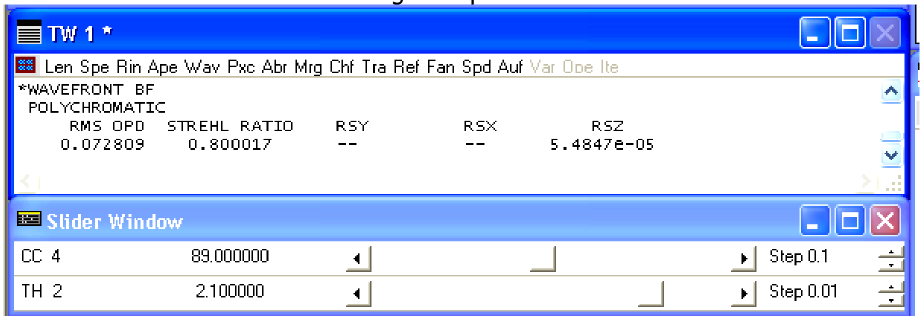

Figure 7. Quality parameters of the aspheric system

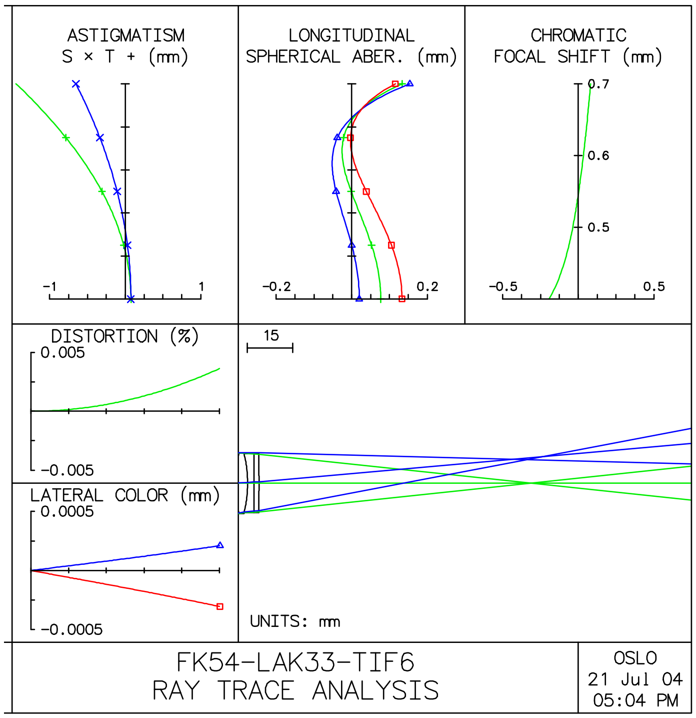

Figure 8. Residual geometric and chromatic aberration of the aspheric system (f/5)

The aspheric system, scaled to exactly f'=100 mm and its quality parameters is presented in figures 9 and 10.

In column, "SPECIAL" (fig. 9) the letter "A" is marked, symbolizing the aspheric character of the fourth surface. The conic constant, equal to 89, being bigger than one, in absolute value, shows that the generating curve is an ellipse.

The characteristics of the generating ellipse need the value of the conic constant and the radius of the osculate circle at the surface vertex. These values are k=89 and r= 378.25 (which is the radius of the initial sphere).

Considering *a* and *b* the half-axis of the ellipse along the optical axis and, respectively, along the y-axis, the following relations are useful:

$$\begin{aligned} k &= \frac{b^2}{a^2} - 1 \\ r &= \frac{b^2}{a} \end{aligned} \quad . \tag{1}$$

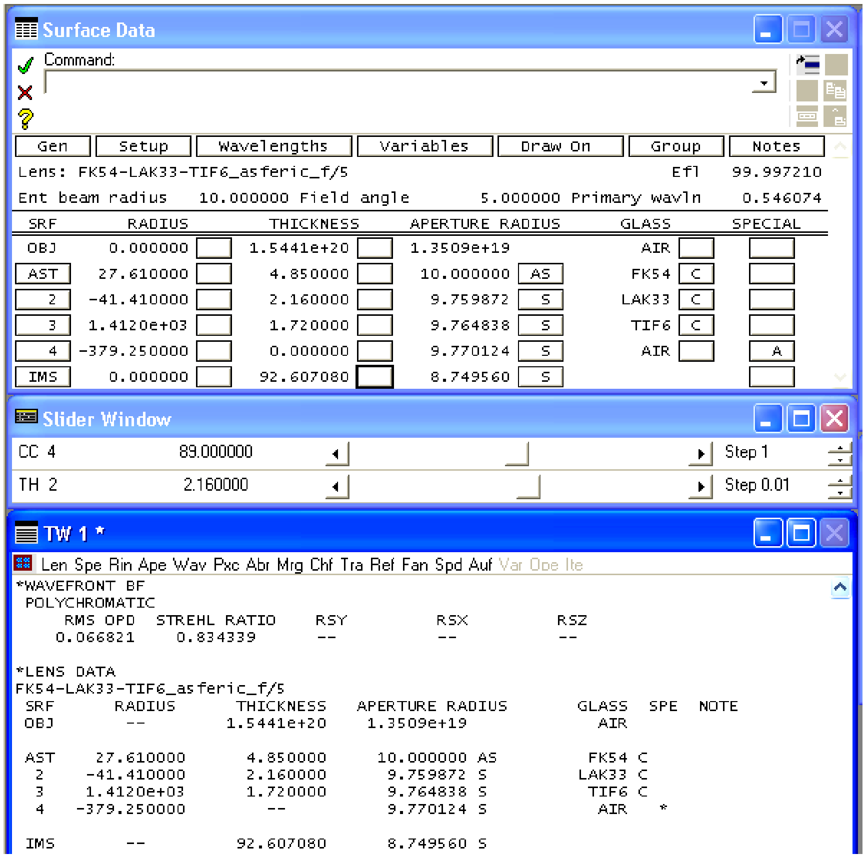

Figure 9. Full data of the scaled aspheric system

Solving the system (1) the solution are:
a=4.31 mm; *b*=40.43 mm.
The equation of the generating ellipse becomes:

$$z = \frac{r\left(1-\sqrt{1-(k+1)\dfrac{y^2}{r^2}}\right)}{k+1} = 28.586\left(1-\sqrt{1-5.56.10^{-4}y^2}\right). \qquad (2)$$

3. Conclusions

Aspheric surfaces bring substantial improvement in image quality for systems, which are mainly affected by spherical aberration. The proper generating noncircular curve is hard to find without specialized soft and need appropriate skills of he human operator.

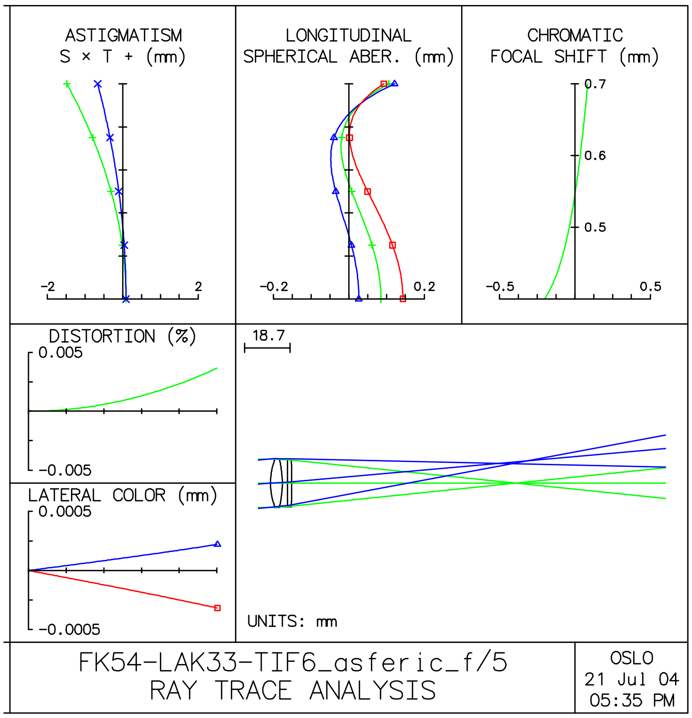

Figure 10. Residual geometrical and chromatic aberrations of aspheric optimized system (f/5)

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