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**Research Article**

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# Thermal optical path difference analysis of the telescope correct lens assembly

**Abstract:** The effect of correct lens thermal optical path difference (OPD) on the optical performance of the Cassegrain telescope system is presented. The correct lens assembly includes several components such as a set of correct lenses, lens mount, spacer, mount barrel, and retainer. The heat transfer from the surrounding environment to the correct lens barrel will cause optical system aberration. The temperature distribution of the baffle is from 20.546°C to 21.485°C. Meanwhile, the off-axis ray's path of the OPD has taken the lens incidence point and emergence point into consideration. The correct lens temperature distribution is calculated by the lens barrel heat transfer analysis; the thermal distortion and stress are solved by the Finite Element Method (FEM) software. The temperature distribution is weighted to each incidence ray path, and the thermal OPD is calculated. The thermal OPD on the Z direction is transferred to optical aberration by fitting OPD into a rigid body motion and the Zernike polynomial. The aberration results can be used to evaluate the thermal effect on the correct lens assembly in the telescope system.

**Keywords:** correct lens; FEM; Off-axis; OPD; ray trace.

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## 1 Introduction

There are many articles [1–7] and discussions about opto-mechanical analysis in telescope design. The heat transfer on the telescope correct lens will cause an optical system aberration increase [2, 4]. The previous studies discussed only cases when temperature was uniformly changed, or linear temperature gradient existed. As the usual case is that temperature is non-uniform, the study on the effect of temperature distribution on the optical performance is required. The numerical method is applied at the present study. The main target is the off-axis ray path in the correct assembly in a Cassegrain telescope, as shown in Figure 1. The correct lens assembly

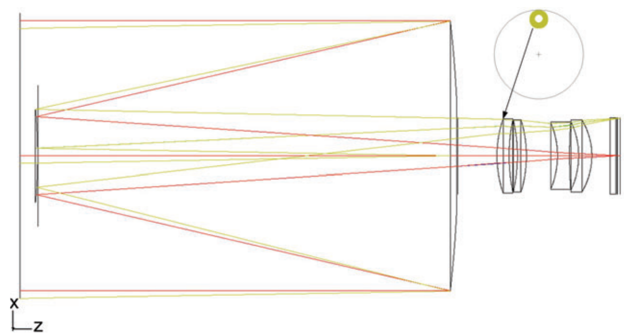


**Figure 1** The telescope system ray traces the profile and off-axis footprint.

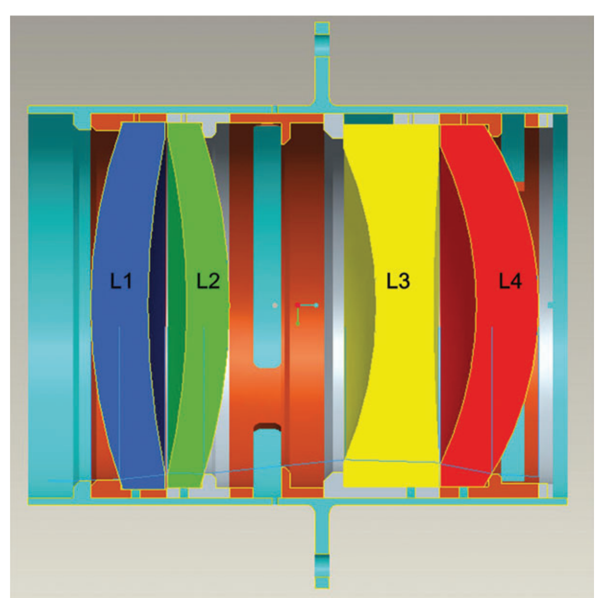


**Figure 2** The correct lens assembly geometric figure.

 

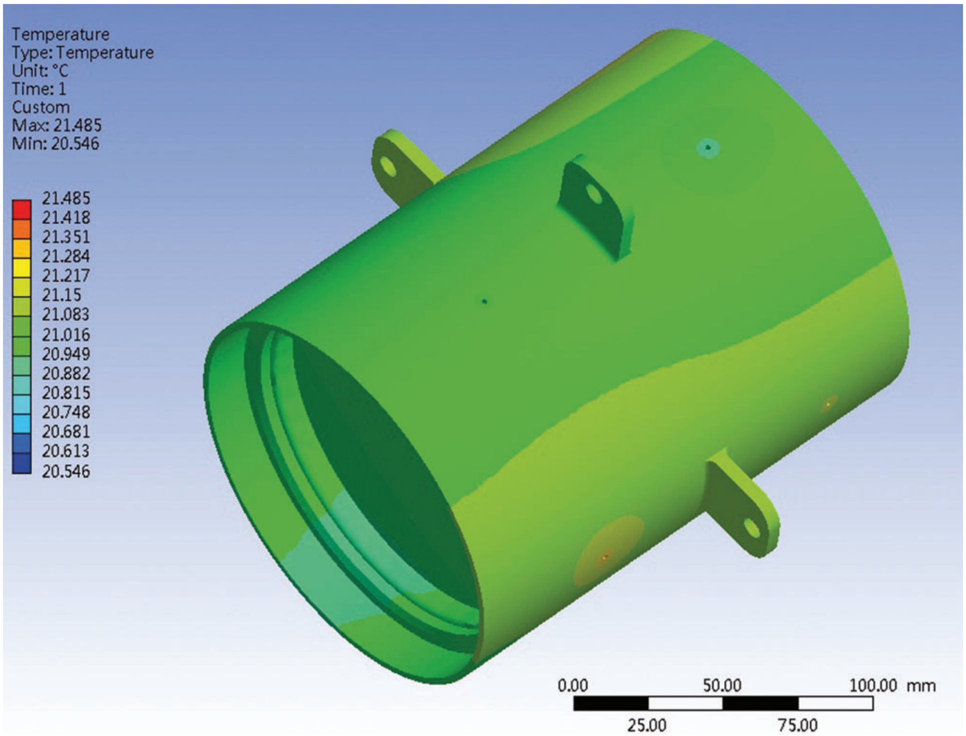


**Figure 3** The correct lens assembly temperature distribution.

geometric figure is shown in Figure 2. There are four lenses in the assembly. The thermal optical path difference (OPD) calculation is calculated through the tracing lens incidence point and emergence point, shown in Figure 1. The temperature distribution of the correct lens component is acquired from the lens mount thermal analysis and is shown in Figure 3. As the temperature change induces the variation of refractive index of the lens component, the temperature distribution is used as a weighting factor to each incidence ray path, and the thermal OPD is calculated individually.

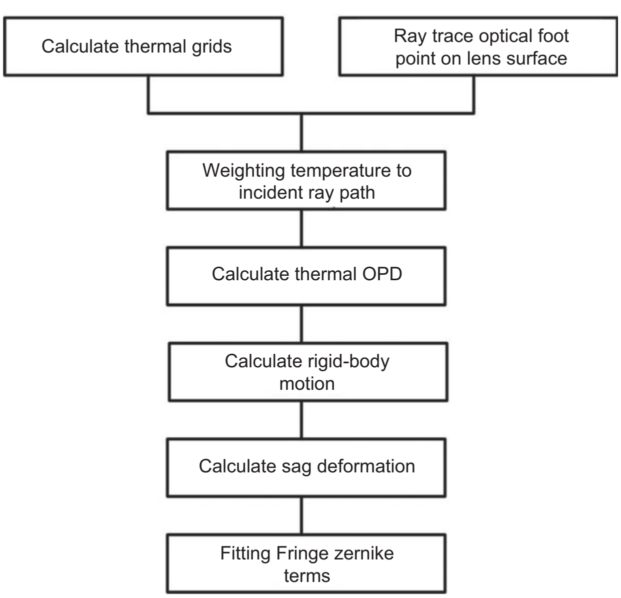


**Chart 1** The numerical method of the off-axis OPD analysis.

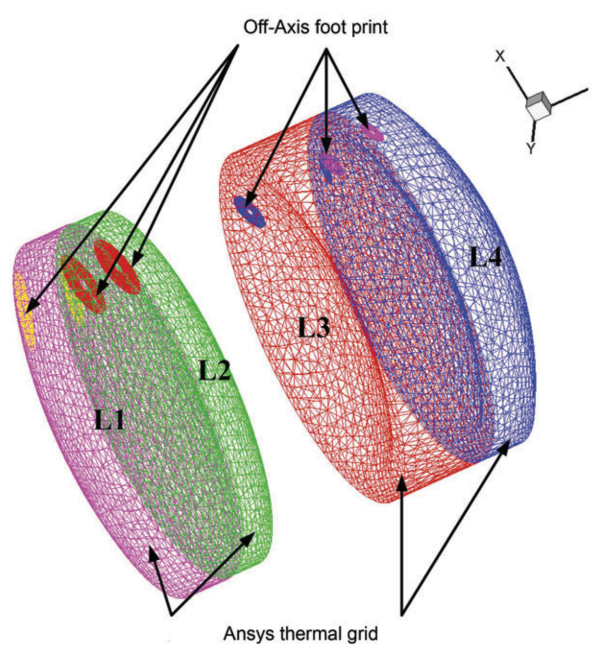


**Figure 4** The correct lens thermal grid and off-axis footprint.

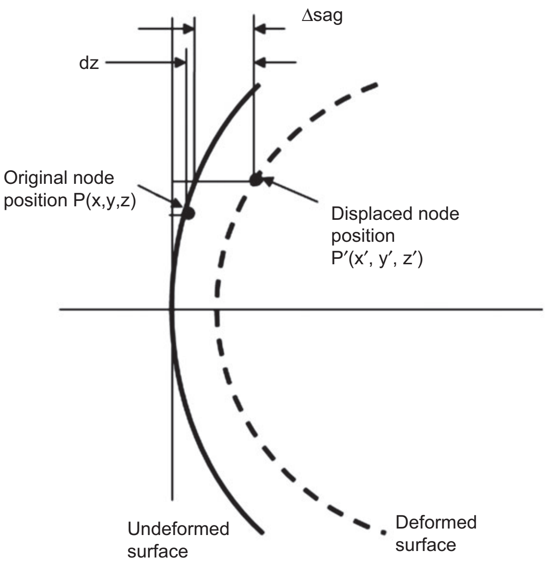


**Figure 5** The thermal OPD at the grid node point needs correction to the optical sag distance.

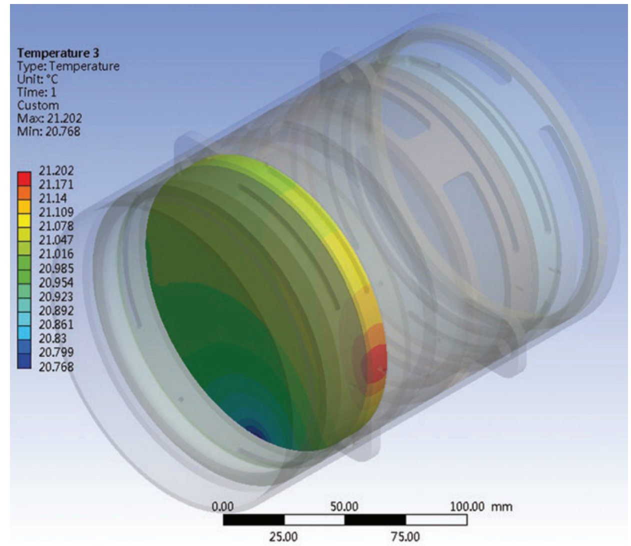


**Figure 7** The correct lens temperature distribution in correct lens L2 temperature.

## 2 Numerical method

The simulation flow chart is shown in Chart 1. The first step is to separately calculate the optical ray trace footprint and temperature distribution, shown in Figure 4. Then, the thermal OPD can be found by Equation (1) where temperature-induced change of the refractive index is considered,

$$\mathrm{OPD} = \sum_{m=1}^{m=\mathrm{total}} \frac{dn}{DT} L_m T_m \tag{1}$$

where $dn/DT$ ($9.9\times10^{-6}$/K) is the thermal-optical coefficient, $L_m$ is the incremental distance traveled by the ray, $T_m$ is the temperature change in each increment, and $m$ is the number of increments. The glass type of the correct lens is fused silica. The lenses have been girded during thermal analysis. There are a lot of nodes for each lens at the numerical model. The increment $m$ is considered for each node.

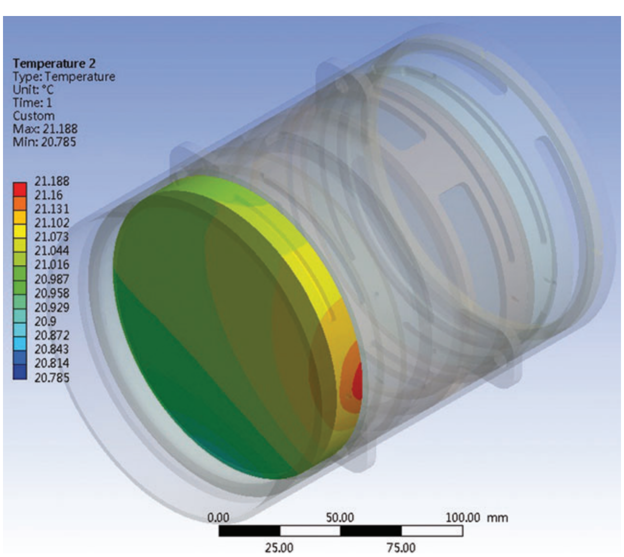


**Figure 6** The correct lens temperature distribution in correct lens L1.

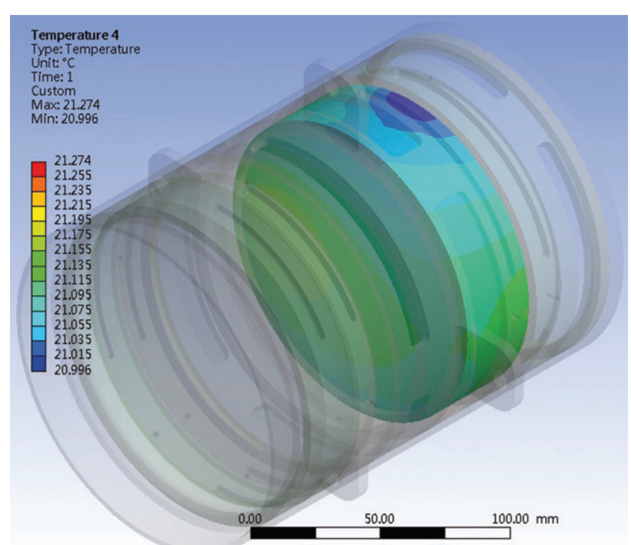


**Figure 8** The correct lens temperature distribution in correct lens L3 temperature.

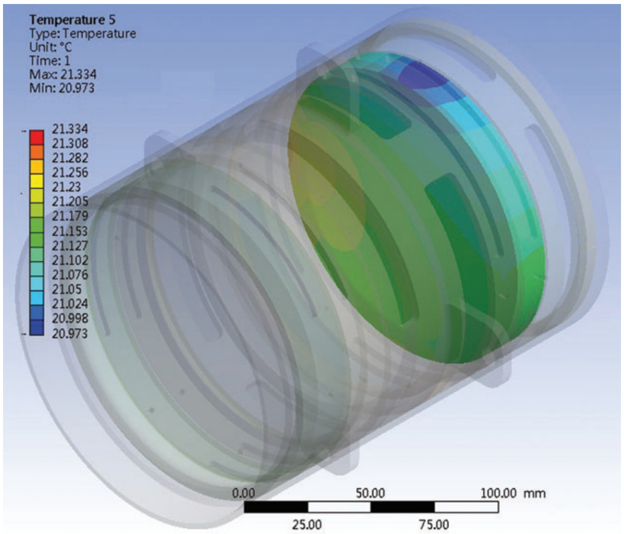


**Figure 9** The correct lens temperature distribution in correct lens L4 temperature.

Thermal OPD has been corrected considering the Z direction OPD to the optical axial sag. The Z direction OPD transfer to the optical sag can be bringing the result into the Zernike polynomial fitting the aberrations. The fitting results will feed into the optical software and evaluate the system aberrations. As shown in Figure 5, the original node point is P(x, y, z); the thermal OPD leads the node point to P′(x′, y′, z′). Therefore, the OPD on the optical axial sag is shown as Equation (2).

$$\Delta sag = P'(x', y') - P(x', y') \tag{2}$$

The thermal OPD result after the correct sag can be used to find the Zernike polynomial coefficients shown as Equation (3),

$$\Delta Z(r,\theta) = A_{00} + \sum_{n=2}^{\infty} A_{n0} R_n^0(r) + \sum_{n=1}^{\infty} \sum_{m=1}^{n} R_n^m \left[A_{nm} \cos(m\theta) + B_{nm} \sin(m\theta)\right] \tag{3}$$

where $\Delta Z(r, \theta)$ is the optical surface at the lens entrance side, r is the radial on the reflection surface, $\theta$ is the azimuth angle, and $A_{nm}$ and $B_{nm}$ are the Zernike coefficients. The equation of the radial dependence of the

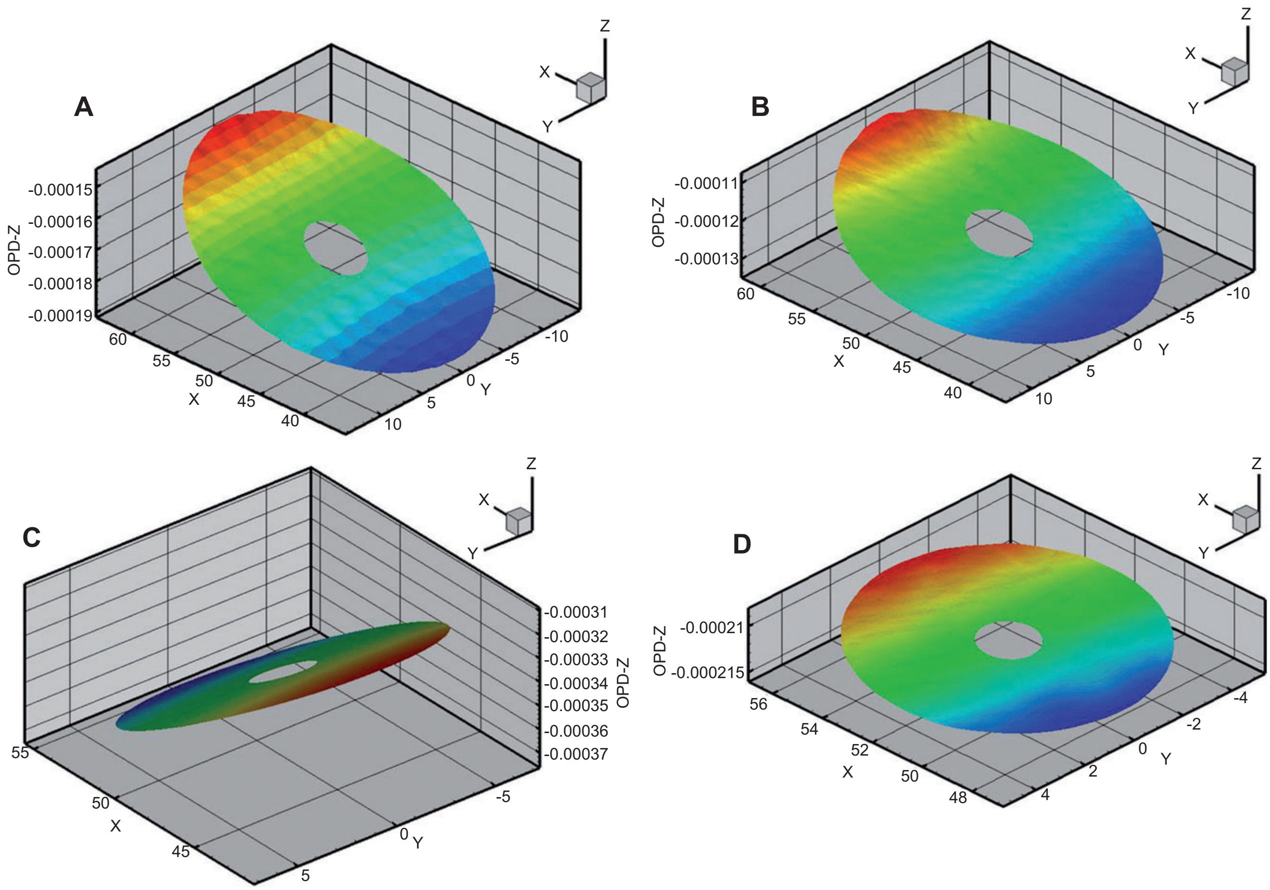


**Figure 10** The correct lens OPD. (A) Correct lens L1 OPD. (B) Correct lens L2 OPD. (C) Correct lens L3 OPD. (D) Correct lens L4 OPD.

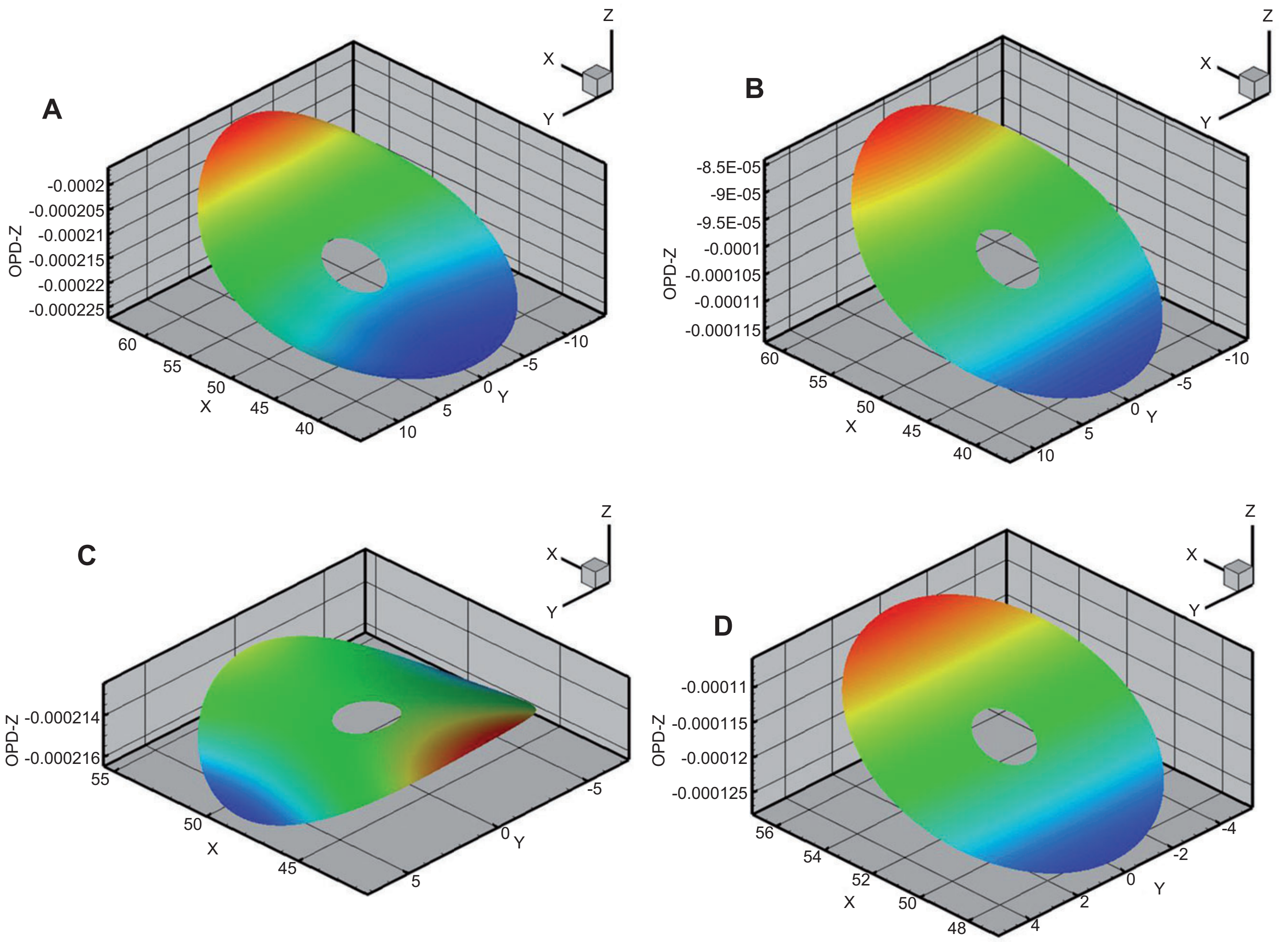


**Figure 11** The correct lens after sag calculation. (A) Correct lens L1 wave front sag. (B) Correct lens L2 wave front sag. (C) Correct lens L3 wave front sag. (D) Correct lens L4 wave front sag.

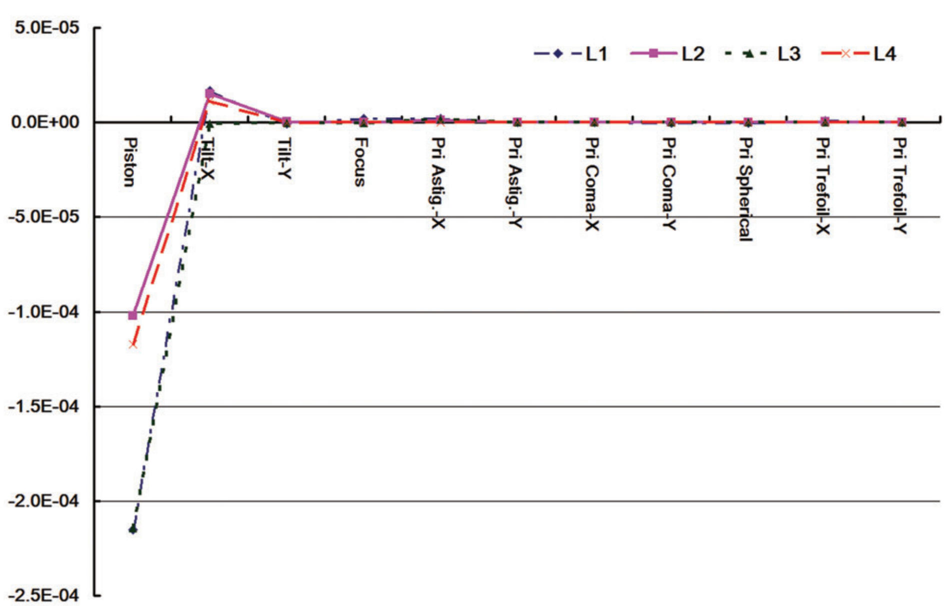


**Figure 12** The correct lens Fringe Zernike fitting result, correct lens L1, L2, L3, and L4.

Zernike polynomial is shown as Equation (4). The Fringe Zernike fitting results are added to the incidence surface. The Fringe Zernike fitting results can be fed into the optical software by the Fringe Zernike sag terms.

$$R_n^m(r)=\sum_{s=0}^{\frac{n-m}{2}}(-1)^s\frac{(n-S)!}{S!\left(\frac{n+m}{2}-S\right)!\left(\frac{n-m}{2}-S\right)!}r^{(n-2S)} \tag{4}$$

## 3 Simulation result

The correct lens temperature distribution is shown in Figures 6–9. The correct lens assembly is inserted into the carbon fiber-reinforced plastic (CFRP) panel and screwed by a flange; L1 and L2 are in the CFRP panel. The CFRP coefficient of thermal expansion (CTE) is $1.16\times10^{-6}$/K. Thus, the L1and L2 temperatures are lower than those of L3 and L4. The system alignment temperature is 20°C. The thermal OPD calculation is shown in Figure 10. The lens' major aberration is the tilt before the OPD sag correction. The thermal OPD result must correlate to the optical sag distance; the results are shown in Figure 11. The lens' major aberration after the sag correction is in L1, L2 and L3 are in the tilt, and L4 is in the astigmatism. Figure 12 shows the Fringe Zernike polynomial fitting results. Besides piston, X-tilt and Astigmatism-X, other optical aberrations are very small. The system aberration is shown in Table 1; the system wave front error is from 0.236 λ increasing to 0.2411 λ; the major Zernike terms are piston tilt and astigmatism.

| Original design | Zemike terms | Thermal OPD |
|---|---|---|
| -0.00083434 | Piston | -0.69279583 |
| 0.04942376 | Tilt-X | 0.04997298 |
| 0 | Tilt-Y | 0.00059932 |
| -0.00999329 | Focus | -0.01191396 |
| 0.02914215 | Pri Astig.-X | 0.03060683 |
| 0 | Pri Astig.-Y | -0.00015342 |
| 0.01063617 | Pri Coma-X | 0.01016947 |
| 0 | Pri Coma-Y | -0.00010046 |
| -0.00932598 | Pri Spherical | -0.00800611 |
| 0.06497329 | Pri Trefoil-X | 0.06565813 |
| PV:0.2360 | @ 546 nm | PV:0.2411 |

**Table 1** The original design and the off-axis OPD wave front error.

## 4 Conclusion

This study employs the thermal conditions to investigate OPD in a correct lens assembly. The thermal boundary condition provides preliminary results; therefore, the thermal gradient is very small. The simulation results provide the following insight:

- The thermal OPD's significant effects are on the piston, tilt, and astigmatism aberration.
- The correct lens, L3, is a biconcave lens, the temperature distribution from the center of the edge is high to low shown in Figure 8; therefore, the tilt affect is insignificant, and the primary thermal OPD aberration is astigmatism. The wave front error will slightly increase.

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