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Aberration Compensation for Telescope Objective System with Reversing Prism Using Binary Optical Element*

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Abstract: The aberration compensation between binary optical len and reversing prism of the hybrid telescope objective is analyzed under the guidance of aberration theory. Phase coefficients of the binary optical element are calculated. Primary configuration of telescope objective with reversing prism is ascertained. The optimized aberration results show that chromatic aberration is rectified exactly at 0. 9 relative pupil height; and maximal longitudinal spherical aberration is within range of tolerance 0. 5 mm and maximal transverse ray aberration value is −0. 115 mm. The MIF with aberration Compensation has been improved largely than the one without aberration compensation.

Key words: Binary optical element; Telescope objective; Aberration compensation; Reversing prism

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0 Introduction

Objectives is the key optical components in telescope system. The imaging quality of objectives will directly influence the overall imaging performance of telescope system. The conventional objectives are generally consist of two or three singlet lens of different material in order to elimilate chromatic aberration and monochromatic aberration. Binary optics develop very rapidly since its rising in 1980s. Binary optical elements have the characters of arbitrary phase distribution and negative dispersion, that mixed with conventional len form binary optical lens or called hybrid lens which not only have the property of aberration compensation but also have the advantages of smaller volume, lighter mass and high diffractive efficiency and so on[1-3]. Thereby, the applicaltion of binary optical lens to the imaging field attracts extreme attention[4]. Telescope objective with reversing prism can be improved through aberration compensation between objective and reversing prism. The conventional objective types include cemented doublet, dialyte and triplet len. Though aberration compensation can be realized between conventional objective and reversing prism, considering the requirement for simplifying structure and adjusting convenience of the telescope objective system, we applied hybrid len to telescope objective to realize the aberration compensation between hybrid len and reversing prism. We get the primary configuration of telescope objective with reversing prism based on aberration theory. After optimization on the primary configuration using CODE V optical design software, we get the aberration results that show chromatic aberration and spherical aberration of hybrid objective system are rectified well. This study performs the design processes of hybrid telescope objective system based on the aberration theory, realizes the aberration compensation between hybrid len and reversing prism. The design results show that primary configuration of the telescope objective is proper. The paper provides the foundation for further hybrid system design under the guideline of aberration theory.

1 Aberration calculating of reversing prism

Generally reversing prisms are applied to telescope objective system in order to obtain the erect image, but negatively the reversing prisms also bring in aberration to the telescope objective. On the analysis for the aberration of reversing prisms, they are usually considered as a equivalent flat glass, reversing prisms aberration can be got through calculating the aberration of equivalent flat glass[5-6]. The optical parameters of a kind of

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objective with reversing prism are as following[6] table 1 (the length of the equivalent flat glass is 160mm, the material is K9):

Table 1 Optical parameters of telescope objective

Focus length/mm	$f=300$
Reletive aperture	$D/f'=1/7.5$
Field of view	$2\omega=6$
Aperture superposition with objective	$f_z=0$

The image side aperture angle of the frist adaxial optical ray of the telescope objective is

$$u'=\frac{D/2}{f'}=\frac{20}{300}=0.066\ 7$$

According to the geometrical optics, the object side aperture angle of the first adaxial optical ray of equivalent flat glass $u=u'=0.066\ 7$. The object side aperture angle of the second adaxial optical ray of the flat glass can be expressed as $u_z=-3°=-0.052\ 4$ obviously. The highness of image at the focus plane of objective can be calculated as follows

$$y'=f'\tan\omega=-300\times\tan(-3°)=15.72\ \mathrm{mm}$$

Lagrange-Helmholtz invariant

$$H=n'u'y'=0.066\ 7\times15.72=1.049$$

Spherical aberration of flat glass

$$S_{P_1}=-d\frac{n^2-1}{n^3}u^4=-160\times\frac{(1.516\ 3)^2-1^2}{(1.516\ 3)^3}\times(0.066\ 7)^4=-1.18\times10^{-3} \tag{1}$$

Coma aberration of flat glass

$$S_{P_2}=S_{P_1}\left|\frac{u_z}{u}\right|=(-1.18\times10^3)\times\left|\frac{-0.052\ 4}{0.066\ 7}\right|=9.27\times10^{-4} \tag{2}$$

Longitudinal chromatic aberration of flat glass

$$S_{PC}=-\frac{d(n-1)}{v\cdot n^2}\times u^2=\frac{160\times(1.516\ 3-1)}{64.1\times(1.516\ 63)^2}\times0.066\ 7^2=-2.49\times10^{-3} \tag{3}$$

2 Analysis on the aberration compensation of hybrid telescope objective

2.1 The basic principle of binary optical element

The phase function of binary optical element is as follows[7-8]

$$\phi(r)=\frac{2\pi}{\lambda}(A_\lambda r^2+G_\lambda r^4+\cdots) \tag{4}$$

Where λ is the primary wavelength, A_λ is the quadratic phase coefficient, decides the paraxial focal power of the element, generally it is applied to rectify chromatic aberration; G_λ is the aspheric phase coefficients, usually applied to rectify monochrome aberration.

For the convex-flat hybrid len (binary element is on the plane), when stop is located on binary len (Fig. 1), its spherical aberration is as follows[9]

$$\Sigma S_{d_1}=\frac{y^4\varphi^3}{4}\left[\left(\frac{n}{n-1}\right)^2+\frac{n+2}{n(n-1)^2}-\frac{4(n+1)}{n(n-1)}+\frac{3n+2}{n}\right]-8mG_\lambda y^4 \tag{5}$$

Where y is the semi-aperture of binary len, φ is the focal power of hybrid len, $n=\infty$ is refractive index of binary len according to the sweatt high refractive index model, m is the diffractive order, usually considered as +1.

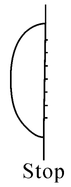

Fig. 1 Convex- flat binary optical len

2.2 Chromatic aberration compensation and calculating of phase coefficient A_λ

The longitudinal chromatic aberration of thin lens with binary optical element is as follows[10]

$$S_{d_c}=h^2\left(\frac{\varphi_{\mathrm{diff}}}{v_{\mathrm{diff}}}+\frac{\varphi_{\mathrm{ref}}}{v_{\mathrm{ref}}}\right)=-S_{P_C} \tag{6}$$

Where h represents the semiaperture, equals 20 mm in the designed hybrid telescope, and the Abbe number for K9 and binary optical elelment is $V_{\mathrm{ref}}=64.1$ and $V_{\mathrm{diff}}=-3.46$, respectively.

The focal power of binary len is as following

$$\varphi=\varphi_{\mathrm{diff}}+\varphi_{\mathrm{ref}}=\frac{1}{300} \tag{7}$$

We can get the value φ_{diff} and φ_{ref} through uniting equation(6)and(7)

$$\varphi_{\mathrm{diff}}=1.499\times10^{-4},\ \varphi_{\mathrm{ref}}=0.003\ 2 \tag{8}$$

The focal power of binary optical element can be written as $\varphi_{\mathrm{diff}}=-2\ mA_\lambda$, when the primary diffractive order is +1, we get coefficient $A_\lambda=-\varphi_{\mathrm{diff}}/2=-7.495\ 5\times10^{-5}$.

2.3 Spherical aberration compensation and calculating of coefficient G_λ

Similarly as the chromatic compensation, we can get the spherical compensation between binary len and reversing prism only have

$$\Sigma S_{d_1}=-\Sigma S_{P_1}=1.18\times10^{-3} \tag{9}$$

Uniting equation(9)and (5), we get

$$G_\lambda=0.367\ 1\times10^{-8}$$

2.4 Coma aberration compensation

Coma aberration of binary len follous convex-flat can be expressed as follows

$$S_{d_2}=-\frac{y^2\varphi^2H}{2}\left[\frac{n+1}{n(n-1)}+\frac{2n+1}{n}\right]=-0.001\ 7 \tag{10}$$

Where φ is the focal power of binary len; y is the semi-diameter of binary len. H is the Lagrange-Helmholtz invariant. The total coma aberration S_2 from the binary optical len and reversing prism, can be written as follows

$$S_2=S_{d_2}+S_{p_2}=-0.004\ 7+0.000\ 927=0.004\ 6 \tag{11}$$

Obviously, the coma aberration is partly compensated between binary len and reversing prism. And the coma aberration can be decreased further through optimizating the curvature of refractive len.

3 Determination of primary configuration

For thin len, the following equation is avalible

$$\varphi=(n-1)\left(\frac{1}{r_1}-\frac{1}{r_2}\right) \tag{12}$$

When considering the plane-convex len(plane is on the second surface or $r_2=\infty$), applying the acquired value $\varphi_{\mathrm{ref}}=0.0032\ \mathrm{mm}^{-1}$, then we get $r_1=161.348$ mm. Because the central thickness of plane-convex len has nothing to do with the focus, we prescribe the central thickness as $d=13$ mm.

For telescope objective without reversing prism, the image distance becomes focus, namely $l=f'$. when reversing prism is considered, image plane will move backward, the moving distance is expressed as follows

$$\Delta l'=d\left(1-\frac{1}{n}\right)=160\times\left(1-\frac{1}{1.5163}\right)=54.48\ \mathrm{mm} \tag{13}$$

When considering the telescope objective with reversing prism as thin len , the distance from objective to image plane is

$$l=f'+\Delta l'=300+54.48=354.48\ \mathrm{mm} \tag{14}$$

We can see from equation (1)~(3) that the movement of equivalent flat glass along optical axis never influence spherical aberration, coma and longitudinal color aberrati-on of telescope objective system. In order to get the objective system more compact, equivalent flat glass should be close to objective, and considering the outline structure design, we describe the distance from telescope objective to the first plane of equivalent flat glass as 10 mm. Because the distance from objective to image plane is 354.48mm as we have calculated, so the length from second plane of equivalent flat glass to image plane is 354.48 − 160 − 10 = 184.48 mm. So far, we have obtained the primary configuration of the telescope objective with reversing prism(Table 2).

Table 2 Initial configuration dutam for telescope objective

Surface #	Surface Type	Y Radius/ mm	Thickness/ mm	Glass
Object	Sphere	Infinity	Infinity	
Stop	Sphere	161.348 0	13.000 0	K9
2	Sphere	Infinity	10.000 0	
3	Sphere	Infinity	160.000 0	K9
4	Sphere	Infinity	184.480 0	
Image	Sphere	Infinity	0.000 0	

4 System optimization and aberration

4.1 System optimazation

Seting the first surface curvature of objective、the distance from second surface of equivalent flat glass to imaging plane 、coefficients A_λ and G_λ as variable, and the foci as a fixed value 300mm, then carrying out optimization programm using the CODE V software on the primary configuration . At last we get the 2-D layout of optimizated telescope objective system as showed in Fig. 2. The configuration dutam of optimizated objective system showed in Table 3.

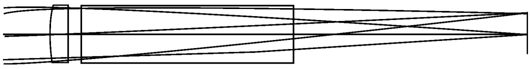

Fig. 2 2-D layout for optimizated objebtive system

Table 3 Configuration dutam for telescope objective after optimazation

Surface #	Surface Type	Y Radius/ mm	Thickness/ mm	Glass
Object	Sphere	Infinity	Infinity	
Stop	Sphere	162.766 8	13.000 0	K9
2	Sphere	Infinity	10.000 0	
3	Sphere	Infinity	160.000 0	K9
4	Sphere	Infinity	175.523 5	
Image	Sphere	Infinity	0.000 0	

The optimizated phase coefficients are as follows

$$A_\lambda=-8.4356\times10^{-5},\ G_\lambda=1.0010\times10^{-8}$$

4.2 Aberration results

The geometric encircled energy cruves(Fig. 3) shows the encircled energy value of the max. field of view at the spot semi-diameter 3.1×10^{-2} mm reaches 0.72, Accordingly the dispersion degree of sopt diagram in the max. field of view caused mainly by the coma aberration is within the acceptable range.

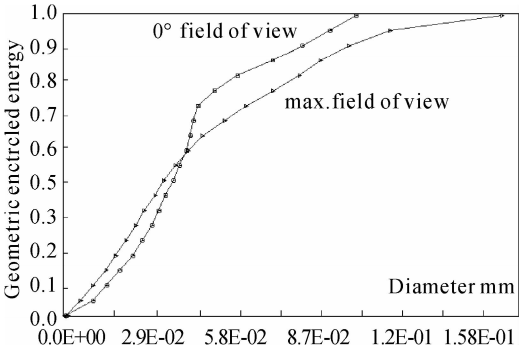

Fig. 3 Circled energy diagram

We can see from three-color longitudinal spherical aberration curves (Fig. 4) that chromatic aberration is rectified exactly at 0.9 relative pupil height, maximal longitudinal spherical aberration is within range of tolerance 0.5 mm. But there are still residual spherochromatism existed in the syetem because of the

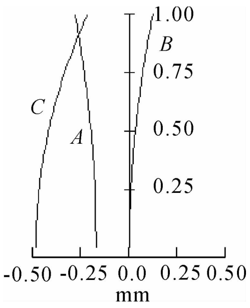

Fig. 4 The three-color longitudinal spherical aber curve.
A stand for wavelength 486 nm;
B stand for the primary wavelegth 589nm;
C stand for wavelength 656 nm.

large negative dispersion of the binary optical element. In the situation of high imaging quality requirement, the imaging performance of telescope system need to be improved further. Comparing the optimizated values A_λ and G_λ with the calculated values, we see that the magnitude of optimizated values is consistent with the calculated ones. It is proved that the calculating results of A_λ and G_λ is reasonable.

Fig. 5 shows the MTF curves without aberration compensation in three different fields of view . From the curves , we can obviously get the conclusion that the system is far away practicality. One reason that lead to the low MTF values lies in only material K9 glass is applied to the telescope objective system, the chromatic aberration from the material can not be eliminated, another reasons casued by the spherical aberration and coma aberration from the telescope objective system (including objective len and reversing prism) also result in the low MTF values.

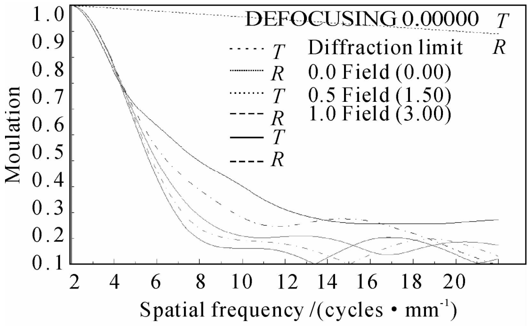

Fig. 5 MTF without aberration compensation using binary optical element

Binary optical element as a kind of special material which has the adverse dispersive property compared to he common glass can compensate for the chromatic aberration and homochromy aberration of telescope objective system. When binary optical element is introduced into telescope objective system, the chromatic aberration and spherical are compensated respectively. The MTF curves with aberration compensation using binary element are showed in Fig. b We can see that the MTF are obviously ameliorated compared to the MTF in Fig. 6. The MTF values in the 1. 5° field of view reach 50% at 20 lp/mm that can be used in general imaging quality telescope objective system (Fig. 6).

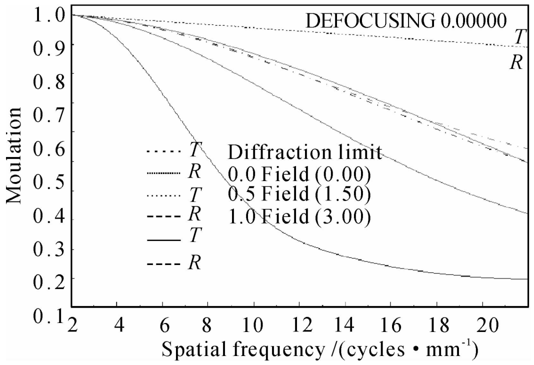

Fig. 6 MTF with aberration compensation using binary element

We can see from the ray aberration curves (Fig. 7) that the maximal meridian ray aberration value in the 3. 0° field of view is −0. 115 mm. The maximal sagittal ray aberration is 0. 04mm. which satisfys the imaging quality requirement of general optical telescope objectives.

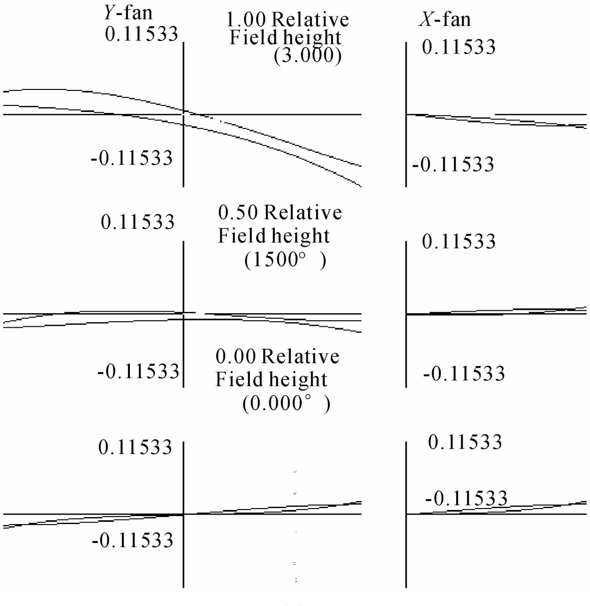

Fig. 7 Ray abbration curves

5 Conclusion

The aberration compensation between binary optical len and reversing prism is investigated. The primary configuration of telescope objective with reversing prism are acquired based on aberration compensation principle. The aberration results of the rectified system after carrying out CODE V software optimization show that the primary configuration we have acquired is proper. The study performs the process of hybrid system design under the direction of aberration throey, has the value of academic guidance.

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二元光学器件实现含转像棱镜望远物镜像差补偿研究

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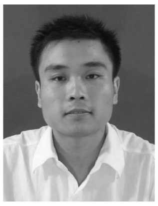
摘　要：以像差理论为指导分析了混合望远物镜中二元光学透镜与转像棱镜之间的像差补偿问题．计算了二元光学器件的相位系数，确定了含补偿棱镜望远物镜的初始结构．用 CODE V 光学设计软件对望远物镜初始结构优化后的像差结果表明：系统色差在 0.9 相对孔径高度得到了校正，纵向球差在容限范围 0.5 mm 之内，最大横向误差为－0.115 mm.

关键词：二元光学器件；望远物镜；像差补偿；转像棱镜



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