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An alignment method for the reflective zoom system by applying vector wavefront aberration theory

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ABSTRACT

The image quality of the reflective zoom system is strongly reduced when the position of the mirror is changed during the zooming process. A new alignment method based on vector wavefront aberration theory is suggested in order to surmount this problem during the zoom process. During the three-mirror reflective zoom system zooming process, the secondary mirror plays an active role and the tertiary mirror plays a complementary role. This feature enables adjustment of the tertiary mirror to compensate for the misalignment of the secondary mirror in the zoom process. The alignment of a three-mirror reflective zoom system was simulated. First, we imposed a feeble maladjustment on the secondary mirror as its position was changed during the zooming process. Then, we obtained the compensation values for the tertiary mirror by using the vector wavefront aberration theory. Lastly, the compensation values were imported to be applied to a misaligned three-mirror reflective zoom system. The image quality of the zoom system prior to and after the application of our proposed alignment method validates its correctness and viability.

1. Introduction

All reflective zoom systems have advantages, such as freedom from chromatic aberration, uniform performance over a broad spectral range, and low weight as compared with refractive zoom systems. As these systems meet space requirements for a wide range of devices, including those used in the fields of remote sensing and space photography, new avenues of research have been opened to design such systems [1]. As the pixel size of a detector decreases, it becomes mandatory for an optical zoom system to possess high resolving power and image quality. In order to meet these requirements, optical designers employ aspheric surfaces in the design of optical systems, which necessitates complex structures and causes these systems to have a high production cost. For optical zoom systems with complex structures, some surfaces become highly sensitive to small errors during the fabrication and assembly processes. When the actual alignment of the designed system is carried out, minor deviations in the parameters greatly affect the image quality of the system. In reflective optical zoom systems, mirrors physically move during the zoom process and their location deviates slightly from the actual zoom position; thereby the image quality of the system is noticeably reduced. Since these optical systems are employed in space research and are required to move in planetary orbits, it is impossible to adjust and align the components of the systems through synthetic or physical means if needed. The computer-aided alignment technique has made it possible to achieve high image quality by correcting the overall system [2]. A mathematical model based on the vector wavefront aberration theory is used in this computer-aided alignment technique. In 1976, R. A. Buchroeder described the vector wavefront aberrations on the basis of the polar coordinate system. Then, Buchroeder [3], Shack [4], Thompson [4,6], and Turne [5] conducted more in-depth studies of aberrations and advanced the development of new aberration technologies. By integrating the vector wavefront aberration theory with interference detection technology, one can obtain data relating to the deviations of the components within an optical system, so this method can be used as a guideline for the alignment of optical systems.

We have established a new alignment model based on the features of the reflective three-mirror optical zoom system. This alignment model is based on the vector wave aberration theory, and uses the mathematical relationships between the designed parameters of a three-mirror optical zoom system, the misalignment values of the secondary mirror, and the wavefront aberrations of the misaligned optical system. The Zernike coefficients representing the third-order coma and astigmatism of the misaligned zoom

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system are obtained using fringe analysis software, which can analyze the interferogram of the field of view, which is obtained through interferometry. The Zernike coefficients thus obtained are inserted into the mathematical relationships described above. These mathematical relationships are used to calculate the compensation values for the tertiary mirror of the zoom system. This new alignment model is then used to simulate a reflective three-mirror optical zoom system by using Zemax software and self-compiled programming to analyze its performance. The simulation results, which are presented in this paper, are of scientific value for their application to alignment technologies for three-mirror optical zoom systems, which are employed in space research and are required to move in planetary orbits.

2. A mathematical model for the vector wave aberration of an optical system

For centered optical systems, the third-order wave aberrations can be expressed in scalar form as given below [7]:

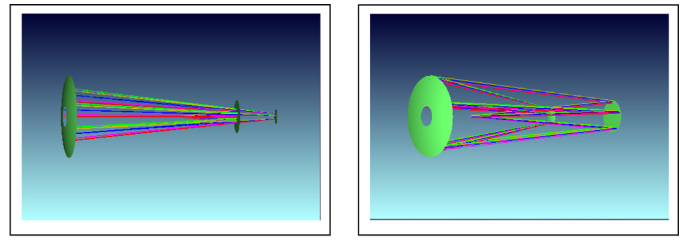
$$W=\sum_j W_{040j}\rho^4+\sum_j W_{131j}H\rho^3\cos\phi+\sum_j W_{220j}H^2\rho^2+\sum_j W_{222j}H^2\rho^2\cos^2\phi+\sum_j W_{311j}H^3\rho\cos\phi, \quad (1)$$

where the coordinate H is the field radius normalized by the image height for the centered system, the coordinate ρ is the entrance pupil radius normalized by the exit pupil radius, the coordinate ϕ is the pupil azimuth with respect to an arbitrarily chosen meridian plane, the index j represents the surface number of the optical element in the optical system, and W_{klm} represents the coefficient of spherical aberration, coma, astigmatism, field curvature, and distortion, respectively.

However, in the misaligned systems, the center of aberrations of various optical surfaces is not coincident with the zero field of the image plane, but there is an offset vector $\boldsymbol{\sigma}_j$, which is the projection of a line connecting the center of the pupil of the jth surface to the center of curvature of that surface and the image plane. Therefore, analogous to the aligned systems, the misaligned systems have an effective field of view $\mathbf{H}_{Aj}$ which is related to the offset vector through the relation $\mathbf{H}_{Aj}=\mathbf{H}_j-\boldsymbol{\sigma}_j$. Therefore, the third-order wave aberrations for the misaligned systems can be expressed in vector form as given below [8,9]:

$$W=\sum_j W_{040j}(\boldsymbol{\rho}\cdot\boldsymbol{\rho})^2+\sum_j W_{131j}\left[\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\cdot\boldsymbol{\rho}\right](\boldsymbol{\rho}\cdot\boldsymbol{\rho})+\sum_j W_{222j}\left[\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\cdot\boldsymbol{\rho}\right]^2+\sum_j W_{220j}\left[\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\cdot\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\right](\boldsymbol{\rho}\cdot\boldsymbol{\rho})+\sum_j W_{311j}\left[\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\cdot\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\right]\left[\left(\mathbf{H}-\boldsymbol{\sigma}_j\right)\cdot\boldsymbol{\rho}\right]. \quad (2)$$

In misaligned systems, the actual positions of the optical elements are disturbed, i.e., decenter and tilt. It is evident from the expression that the disturbance of the position of the optical elements will not affect the spherical aberration but contribute significantly to the coma and astigmatic wave aberrations in the optical systems [3–5]. In order to simplify the analytical process while analyzing the vector wave aberrations of the misaligned systems, we pay more attention to these two aberrations.



(a) (b)

Fig. 1. Optical path through the system: (a) short-focus, (b) long-focus.

Table 1
Parameters of components of the TMRS.

Mirror	Radius (mm)	Conic constant	Separation (mm)
1 (STO)	47	0.490	−100/−158
2	−139	0.058	138/88
3	789	1.099	−109/−48
4	Infinity	0	0

Table 2
Parameters of on-axis TMRS.

Parameters	Long-focus	Short-focus
Focal length (mm)	50	20
Field	0 – 1°	0 – 2°
Wavelength (nm)	486–850	

Under the condition of disturbance of the optical elements, the two aberrations in vector form can be expressed by the formulae given below:

$$W_{coma}=\sum_{j=1}^{n}W_{131j}\left[(\mathbf{H}-\boldsymbol{\sigma})\cdot\boldsymbol{\rho}\right](\boldsymbol{\rho}\cdot\boldsymbol{\rho}), \quad (3)$$

$$W_{ast}=\sum_{j=1}^{n}W_{222j}\left[(\mathbf{H}-\boldsymbol{\sigma})\cdot\boldsymbol{\rho}\right]^2. \quad (4)$$

In real optical systems, Zernike coefficients are normally useful in assessing the image quality of the system. These coefficients are obtained by Zernike polynomial fitting to the interference fringe pattern obtained as an interferogram through an interference detection system. The relationships between Zernike coefficients and coma and astigmatism for the misaligned optical systems are given in the following two formulae [10]:

$$W_{coma}=\sqrt[3]{Z_7^2+Z_8^2}^{\,i\left[tg^{-1}\left(\frac{Z_8}{Z_7}\right)\right]}, \quad (5)$$

$$W_{ast}=\sqrt[2]{Z_5^2+Z_6^2}^{\,i\left[tg^{-1}\left(\frac{Z_6}{Z_5}\right)\right]}. \quad (6)$$

By combining Eqs. (3–6), the equation for the offset vector can be obtained. Through the coupling relationship between the offset vector and tilts and decenters [9], one can obtain the values of tilt and decenter for each optical component in the system, which can guide the alignment of optical systems.

3. Simulation model

3.1. Three-mirror reflective zoom system

In order to perform the simulation experiments, we designed an on-axis three-mirror reflective zoom system (TMRZS) with multiple aspheric mirrors. Fig. 1 shows the optical path of the TMRZS and