Third-order coma-free point in two-mirror telescopes by a vector approach

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In this paper, two-mirror telescopes having the secondary mirror decentered and/or tilted are considered. Equations for third-order coma are derived by a vector approach. Coma-free condition to remove misalignment-induced coma was obtained. The coma-free point in two-mirror telescopes is found as a conclusion of our coma-free condition, which is in better agreement with the result solved by Wilson using Schiefspiegler theory. © 2011 Optical Society of America

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1. Introduction

The two-mirror telescopes are widely employed in astronomy research. Before any telescope can go into operation, it must be aligned with sufficient accuracy. A perfectly collimated two-mirror telescope will produce no coma on axis. If the secondary mirror is decentered and/or tilted, field-constant coma will be introduced. Freedom from coma is the fundamental condition for the alignment of modern telescopes [1,2]. For any two-mirror telescope system, there will be a point somewhere on the primary mirror axis rotating the secondary mirror about which no coma will be introduced. This is called the "coma-free point" (CFP) [3–5]. This property is used in collimating slow focal ratio two-mirror telescopes purely by tilting the secondary mirror. Although the CFP has been found by some means or other, we concern ourselves with the nature of the decentering aberration function.

The general nature of the decentering aberration function was analyzed in a fundamental paper by Shack and Thompson [6]. Shack established a vector expression for the wave aberration expansion that made use of a vector operation to give a concise description of the third-order aberration field performance in a perturbed telescope. This earlier work by Shack has been developed by Thompson, who extended the vector formulation for wavefront aberration dependence on field and aperture up to fifth order [7,8]. The misalignment-induced aberration fields of telescopes are discussed using Shack's vector expression by some earlier works [9,10]. Particular attention is given to astigmatism when misalignment-induced coma is removed. Noethe derived the analytical expressions for the CFP of two-mirror systems with stop positions anywhere [11]. Rakich had a paper on this subject using Plate Diagram approach [12]. However, we solve this problem by use of the vector aberration theory conceived by Shack.

Without fast numerical apertures or significant field sizes, the third-order approximation is adequate to describe the aberrations of telescopes. In this work, equations for third-order coma in perturbed two-mirror telescopes are derived via a vector approach conceived by Shack. Two sets of third-order coma, introduced by the base sphere and aspheric departure of the secondary mirror, respectively, are given in Section 2. These two sets can cancel each other as a result of coma-free condition presented in Section 3. Thus, the coma due to translation of

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secondary mirror and the coma due to rotation of secondary mirror can cancel out. The CFP derived from our coma-free condition is proved to be identical to the result found by Wilson [4].

2. Misalignment-Induced Field-Constant Coma

A. Vector Approach

The wavefront aberration function can be expanded as a scalar function of two vectors, normalized aperture vector $\vec{\rho}$ in exit pupil plane, which specifies any point in system aperture, and normalized field vector $\vec{H}$, which specifies any point in the system field of view. The wave aberration term for third-order coma of jth surface contributions is [4]

$$W_{\mathrm{coma},j} = W_{131,j} H \rho^3 \cos\phi, \tag{1}$$

where ϕ is the azimuth angle of the plane containing the ray and the principal ray in the image forming the wavefront [13,14]. The corresponding vector form is

$$W_{\mathrm{coma},j} = W_{131,j}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}). \tag{2}$$

Third-order coma of the system is obtained by summing up the surface contributions:

$$W_{\mathrm{coma}} = \sum_j W_{\mathrm{coma},j}. \tag{3}$$

In a perturbed system, each optical surface introduces aberration contributions of the same form as the surface contributions in a rotationally symmetric system, but the component field vectors $\vec{H}_j$ are measured from centers of symmetry that do not coincide for each surface contribution. Furthermore, two independent sets of aberrations are introduced by each surface: one by the base sphere and the other by the aspheric departure of the surface. As we see in Subsection 2.B, centers of symmetry do not coincide for the spherical and aspheric contributions for each surface. Aspheric contribution to the aberration field associated with a surface must be treated separately from spherical contribution when analyzing the perturbed system. These two sets of aberration terms can be combined vectorially to yield the final aberration contribution for the surface. The system aberration description obtained by adding the surface contributions together must be described as a function of a field vector $\vec{H}$, which is measured from an arbitrarily chosen field center. If the displacement of the surface component center of symmetry from the field center is measured by the vector $\vec{\sigma}_j^o$ and $\vec{\sigma}_j^*$, then

$$\vec{H}_j^o = \vec{H} - \vec{\sigma}_j^o, \tag{4a}$$

$$\vec{H}_j^* = \vec{H} - \vec{\sigma}_j^*, \tag{4b}$$

as illustrated in Fig. 1. The superscript o denotes the base sphere component and the superscript $*$ denotes the aspheric component in this work.

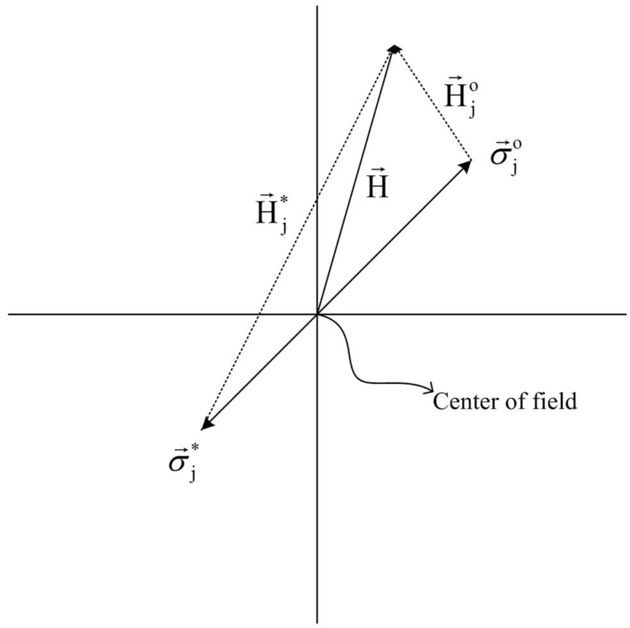

Fig. 1. Field displacement vectors for surface contribution. $\vec{\sigma}_j^o$ is for the center of symmetry for the base sphere, and $\vec{\sigma}_j^*$ is for the center of symmetry for the aspheric departure of the jth surface.

The summation can then be carried out as a vector operation, giving the resultant system aberrations as a function of the field vector $\vec{H}$ and terms involving the displacement vectors $\vec{\sigma}_j^o$ and $\vec{\sigma}_j^*$. We can find that

$$\begin{aligned} W^o_{\mathrm{coma},j} &= W^o_{131,j}(\vec{H}^o_j\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &= W^o_{131,j}[(\vec{H}-\vec{\sigma}^o_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}), \end{aligned} \tag{5a}$$

$$\begin{aligned} W^*_{\mathrm{coma},j} &= W^*_{131,j}(\vec{H}^*_j\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &= W^*_{131,j}[(\vec{H}-\vec{\sigma}^*_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}), \end{aligned} \tag{5b}$$

$$\begin{aligned} W_{\mathrm{coma},j} &= W^o_{\mathrm{coma},j} + W^*_{\mathrm{coma},j} \\ &= W^o_{131,j}[(\vec{H}-\vec{\sigma}^o_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}) \\ &\quad + W^*_{131,j}[(\vec{H}-\vec{\sigma}^*_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}) \\ &= (W^o_{131,j} + W^*_{131,j})(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &\quad - [(W^o_{131,j}\vec{\sigma}^o_j + W^*_{131,j}\vec{\sigma}^*_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}) \\ &= W_{131,j}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &\quad - [(W^o_{131,j}\vec{\sigma}^o_j + W^*_{131,j}\vec{\sigma}^*_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}). \end{aligned} \tag{6}$$

From Eq. (6), third-order coma is organized into two subgroups: the first term $W_{131,j}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho})$ is the linear coma for surface contributions and the second term $-[(W^o_{131,j}\vec{\sigma}^o_j + W^*_{131,j}\vec{\sigma}^*_j)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho})$ is the constant coma surface contributions.

B. Locating the Centers of Symmetry

The lateral misalignment of two-mirror telescope involves a displacement of the secondary mirror optical axis without any significant change in the mirror spacing and takes the form of tilt and decenter of the secondary mirror with respect to the primary mirror, as shown in Fig. 2.

The aberration field contribution of a spherical surface is centered on the line connecting the center of the pupil, for that surface, with its center of curvature. When an aspheric is placed onto a surface, it provides an additional contribution to the aberration field at the image plane. The center of the aberration contribution due to the aspheric is along the line connecting the vertex of the aspheric cap with the center of the pupil, respectively [6]. Consider the misalignment case illustrated in Fig. 2, where the secondary mirror is tilted and decentered in the meridian plane. Following the descriptions given in [6], the field centers of the spherical and aspheric components of the primary and secondary mirrors are located in Fig. 2. The stop is at the primary mirror; no aspheric contribution of the primary mirror is present. The spherical field center of primary mirror forms at c_1, where the line through the curvature center of the secondary mirror (C_2) and the image field center of the primary mirror (I_1) intersect with the final image plane (I_2). As the optical axis ray, by definition, passes through the center of its associated object/image plane and the entrance/exit pupil for each surface in the system [7,15], it intersects I_2 at c_1, and c_1 is arbitrarily chosen as the center of field. While coma induced by tilt and decenter is zero, c_1 is also the "axial point," which does not coincide with the mechanical axis (pointing error in two-mirror telescopes).

The line through C_2 and the center of entrance pupil center (E_1) intersects I_2 at the point c_2, which is the spherical field center symmetry of the secondary mirror. The exit pupil center E_2 of secondary mirror is also located on this line. The line from E_2 through the aspheric vertex of the secondary mirror (V_2) locates the point c_3, which is the field center of symmetry of the aspheric component of secondary mirror.

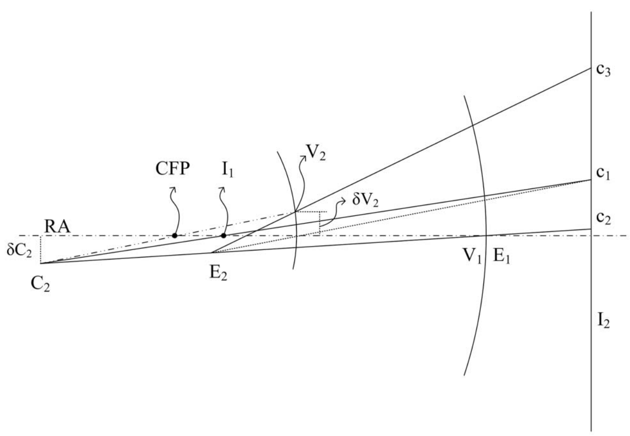

Fig. 2. Tilted and decentered two-mirror telescope: the stop is at the primary mirror; tilt and decenter are both in the meridian plane.

C. Third-Order Coma

As described in Subsection 2.B, c_1 is aberration center of symmetry for the primary mirror and the center of field arbitrarily chosen, i.e., $\vec{\sigma}_1^o = \vec{\sigma}_1^* = 0$ for the primary mirror, and the third-order coma for primary mirror contribution is then

$$\begin{aligned} W_{\text{coma},1} &= (W_{131,1}^o + W_{131,1}^*)(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &= W_{131,1}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}). \end{aligned} \tag{7a}$$

The stop is at primary mirror, so that the primary mirror aspheric coefficient does not affect the aberrations dependence on field, i.e., $W_{131,1}^* = 0$.

Both the centers of symmetry for base sphere and aspheric of secondary mirror contributions do not coincide with that for the primary mirror, which we chose as the field center. The third-order coma for the secondary mirror contribution is then given by

$$\begin{aligned} W_{\text{coma},2} &= W_{131,2}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &\quad - [(W_{131,2}^o\vec{\sigma}_2^o + W_{131,2}^*\vec{\sigma}_2^*)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}). \end{aligned} \tag{7b}$$

Here, the $\vec{H}$ and sigma vectors in the image plane use the exit pupil of the two-mirror system and the lines through the middle of this pupil to the center of curvature and surface vertex of the secondary mirror for spherical and aspherical contributions, respectively.

The total third-order coma for a perturbed two-mirror telescope is obtained by summing up primary mirror contribution Eq. (7a) and secondary mirror contribution Eq. (7b), as shown in Eq. (8):

$$\begin{aligned} W_{\text{coma}} &= W_{\text{coma},1} + W_{\text{coma},2} \\ &= (W_{131,1} + W_{131,2})(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\ &\quad - [(W_{131,2}^o\vec{\sigma}_2^o + W_{131,2}^*\vec{\sigma}_2^*)\cdot\vec{\rho}](\vec{\rho}\cdot\vec{\rho}). \end{aligned} \tag{8}$$

The first term in Eq. (8) is the same as third-order coma for a centered two-mirror telescope before tilt and decenter are imposed; the second term is the decentering coma, which is constant in both magnitude and direction over the field of view. $-(W_{131,2}^o\vec{\sigma}_2^o + W_{131,2}^*\vec{\sigma}_2^*)$ is wave aberration coefficient for third-order constant coma, which contain base sphere contribution and aspheric contribution. If the coma is corrected in the centered telescope (e.g., Ritchey–Chrétien, Schwarzschild and Couder forms), then Eq. (8) reduces to a constant value of coma over the field.

The calculation of decentering coma in Eq. (8) is presented in Subsections 2.C.1 and 2.C.2. Sign conventions will follow the standard optical practice [4], as illustrated in Fig. 3, where P' is the image side principal plane, d_1 is the intermirror distance, f_1' is the primary focal length, f' is the system focal length, C_2 is the curvature center of secondary mirror, I_1 is the focus point of primary mirror, I_2 is the position of the final image, y_1 is the paraxial aperture ray

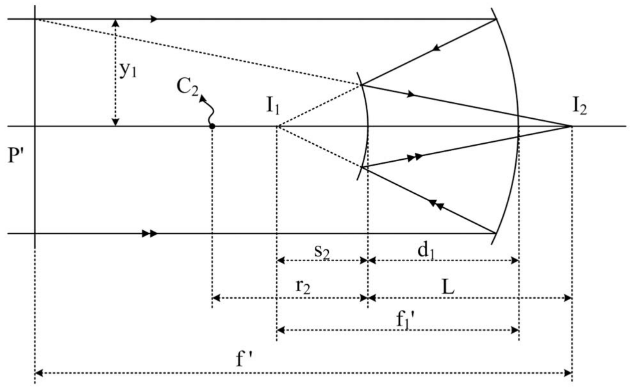

Fig. 3. Gaussian optics of a Cassegrain two-mirror telescope.

height, and s_2 and L are the object and image distances for the secondary mirror, respectively.

In our case, tilt and decenter are coplanar, and $\vec{\sigma}_2^o$ and $\vec{\sigma}_2^*$ are collinear. Here we just have to consider the sign of $\vec{\sigma}_2^o$ and $\vec{\sigma}_2^*$. The vector equations with $\vec{\sigma}_2^o$ and $\vec{\sigma}_2^*$ are expressed in scalar form.

1. Base Sphere Contribution

To simplify the calculation, we assume that the aspheric vertex V_2 of the secondary mirror is fixed, as shown in Fig. 4. The axis of the primary mirror intersects the final image plane at the point o.

Based on similar triangles theorem, we can derive:

$$oc_1 = \frac{(L - s_2)(-\delta C_2)}{s_2 - r_2}, \tag{9a}$$

$$oc_2 = -\frac{(L + d_1)(-\delta C_2)}{d_1 + r_2}, \tag{9b}$$

$$\begin{aligned} c_1c_2 &= oc_2 - oc_1 \\ &= \left(\frac{L - s_2}{s_2 - r_2} + \frac{L + d_1}{d_1 + r_2}\right)\delta C_2 \\ &= \left[\frac{(L - r_2)(d_1 + s_2)}{(s_2 - r_2)(d_1 + r_2)}\right]\delta C_2. \end{aligned} \tag{10}$$

The maximum field height is $u_{\mathrm{pr}1}f'$ (normalized to 1). $u_{\mathrm{pr}1}$ is the semiangular field in object space, and f' is the effective focal length. Normalizing c_1c_2, we can obtain the fractional displacement vector $\vec{\sigma}_2^o$ by

$$\vec{\sigma}_2^o = \frac{c_1c_2}{u_{\mathrm{pr}1}f'}. \tag{11}$$

The conversion of Seidel coefficient for coma to wavefront aberration for third-order coma is given by

$$W'_{131} = \frac{1}{2}\left(\frac{y_1}{y_{m1}}\right)^3\left(\frac{\eta'}{\eta'_m}\right)\sum S_{\mathrm{II}}\cos\phi, \tag{12}$$

where y_{m1} and η'_m are the normalized paraxial aperture ray height and normalized image height, respectively. y_1 and η' are the real paraxial aperture ray height and real image height [13,14], respectively. S_{II} is the Seidel coefficient for coma. Comparing Eq. (12) with Eq. (1), we obtain the wavefront aberration coefficients:

$$W_{131,j} = \frac{1}{2}(S_{\mathrm{II}})_j. \tag{13}$$

Then, we have

$$W^o_{131,2} = \frac{1}{2}(S_{\mathrm{II}})^0_2, \tag{14a}$$

$$W^*_{131,2} = \frac{1}{2}(S_{\mathrm{II}})^*_2. \tag{14b}$$

Then, wave aberration coefficients for third-order constant coma can be written as

$$W^o_{131,2}\vec{\sigma}^o_2 = \frac{1}{2}(S_{\mathrm{II}})^0_2\vec{\sigma}^o_2, \tag{15a}$$

$$W^*_{131,2}\vec{\sigma}^*_2 = \frac{1}{2}(S_{\mathrm{II}})^*_2\vec{\sigma}^*_2, \tag{15b}$$

which recombine existing aberration coefficients into new third-order constant coma coefficients. For small tilt and decenter effects acceptable in practice, the third-order formulae given above are extremely accurate. The Seidel coefficient for third-order coma of the secondary mirror is given by [4]

$$(S_{\mathrm{II}})_2 = \left(\frac{y_1}{f'}\right)^3\left[-d_1\xi + \frac{f'}{2}(m_2^2 - 1) - s_{\mathrm{pr}1}\frac{L}{f'}\xi\right]u_{\mathrm{pr}1}, \tag{16}$$

where

$$\xi = \xi^0 + \xi^* = \frac{(m_2+1)^3}{4}\left(\frac{m_2-1}{m_2+1}\right)^2 + \frac{(m_2+1)^3}{4}b_{s2}. \tag{17}$$

b_{s2} is the Schwarzschild (conic) constant, $s_{\mathrm{pr}1}$ is the distance from the first surface to the entrance pupil, and m_2 is the magnification of the secondary mirror. The entrance pupil was defined as being at the primary mirror, i.e., $s_{\mathrm{pr}1} = 0$. Then, we get

$$\begin{aligned} (S_{\mathrm{II}})^0_2 &= \left(\frac{y_1}{f'}\right)^3\xi^0\left[-d_1 + \frac{2f'}{m_2 - 1}\right]u_{\mathrm{pr}1} \\ &= -\frac{1}{4}\left(\frac{y_1}{f'}\right)^3(1 - m_2^2)(d_1 + L + f')u_{\mathrm{pr}1}, \end{aligned} \tag{18a}$$

$$\begin{aligned} (S_{\mathrm{II}})^*_2 &= -\left(\frac{y_1}{f'}\right)^3\xi^* d_1 u_{\mathrm{pr}1} \\ &= -\frac{1}{4}\left(\frac{y_1}{f'}\right)^3(m_2+1)^3 b_{s2} d_1 u_{\mathrm{pr}1}. \end{aligned} \tag{18b}$$

$(S_{II})^0_2$ gives contribution due to a spherical surface, $(S_{II})^*_2$ gives contribution due to the aspheric form.

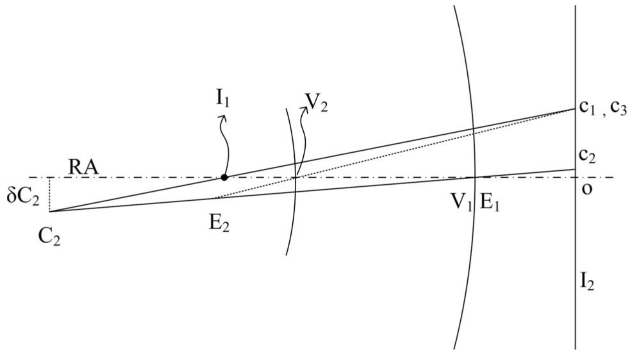

Fig. 4. Pure decenter of the center of curvature of the secondary mirror C_2.

Applying Eqs. (10), (18a), and (11) to Eq. (15a), we have

$$-W^o_{131,2}\vec{\sigma}^o_2 = \frac{1}{8}\left(\frac{y_1}{f'}\right)^3 (1-m_2^2)(d_1+L+f')u_{\mathrm{pr1}}\frac{c_1c_2}{u_{\mathrm{pr1}}f'}$$
$$= -\frac{1}{8}\left(\frac{y_1}{f\prime}\right)^3 (1-m_2^2)(m_2+1)\delta C_2. \qquad (19)$$

2. *Aspheric Contribution*

Similar to the manner used in Subsection 2.C.1., we assume that the center of curvature of the secondary mirror C_2 is unchanged, as shown in Fig. 5.

Using similar triangles theorem, we can obtain

$$\frac{\delta V_2}{c_1c_3} = \frac{-(s_2')_E}{L-(s_2')_E}, \qquad (20)$$

where $-(s_2')_E$ is the exit pupil distance from secondary mirror, given as

$$(s_2')_E = \frac{d_1 f_2'}{d_1+f_2'}. \qquad (21)$$

Then, c_1c_3 is derived from Eq. (13):

$$c_1c_3 = \frac{L-(s_2')_E}{-(s_2')_E}\delta V_2 = \left[1-\frac{L(d_1+f_2')}{d_1f_2'}\right]\delta V_2. \qquad (22)$$

Normalizing c_1c_3, we obtain the fractional displacement vector $\vec{\sigma}^*_2$:

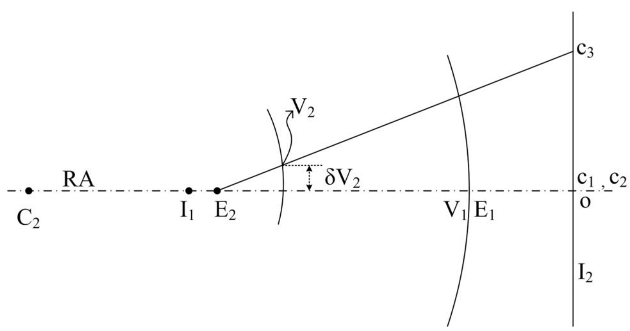

Fig. 5. Pure decenter of the aspheric vertex V_2 of the secondary mirror.

$$\vec{\sigma}^*_2 = \frac{c_1c_3}{u_{\mathrm{pr1}}f'}. \qquad (23)$$

Applying Eqs. (22), (18b), and (23) to Eq. (15b), we obtain

$$-W^*_{131,2}\vec{\sigma}^*_2 = \frac{1}{8}\left(\frac{y_1}{f'}\right)^3 (m_2+1)^3 b_{s2} d_1 u_{\mathrm{pr1}}\frac{c_1c_3}{u_{\mathrm{pr1}}f'}$$
$$= -\frac{1}{8}\left(\frac{y_1}{f'}\right)^3 (m_2+1)^3 b_{s2}\delta V_2. \qquad (24)$$

3. **Coma-Free Condition**

Now, considering the case of Fig. 1, lateral misalignment of the secondary mirror can be represented by the separation of the two optical axes at the center of curvature C_2 and the aspheric vertex V_2. From Eqs. (19) and (24), we know that misalignment coma is proportional to the separation δC_2 and δV_2, respectively, for base sphere and aspheric departure contributions. The total third-order constant coma is obtained by summing up Eqs. (19) and (24):

$$\begin{aligned}-(W^o_{131,2}\vec{\sigma}^o_2 + W^*_{131,2}\vec{\sigma}^*_2) &= -\frac{1}{8}\left(\frac{y_1}{f'}\right)^3 (1-m_2^2)\\ &\quad\times (m_2+1)\delta C_2 - \frac{1}{8}\left(\frac{y_1}{f'}\right)^3\\ &\quad\times (m_2+1)^3 b_{s2}\delta V_2\\ &= -\frac{1}{8}\left(\frac{y_1}{f'}\right)^3 (m_2+1)^2\\ &\quad\times [(1-m_2)\delta C_2\\ &\quad+ (m_2+1)b_{s2}\delta V_2]. \qquad (25)\end{aligned}$$

There is a pivot point rotating the secondary mirror about which the base sphere contribution and aspheric contribution in Eq. (25) will cancel out. The total system third-order coma will remain unchanged across the field.

The coma-free condition is then given by solving for the zero of Eq. (25):

$$(1-m_2)\delta C_2 + (m_2+1)b_{s2}\delta V_2 = 0. \qquad (26)$$

We can derive the CFP from Eq. (26), which can also be written as

$$\frac{\delta C_2}{\delta V_2} = \frac{m_2+1}{m_2-1}b_{s2} = \frac{r_2 - z_{\mathrm{CFP}}}{-z_{\mathrm{CFP}}}. \qquad (27)$$

z_{CFP} is the distance from secondary mirror to the CFP, which is derived from Eq. (27), as shown in Fig. 2:

$$z_{\mathrm{CFP}} = r_2/\left[1-\left(\frac{m_2+1}{m_2-1}\right)b_{s2}\right]$$
$$= s_2/\left[\left(\frac{m_2+1}{2m_2}\right)\left\{1-\left(\frac{m_2+1}{m_2-1}\right)b_{s2}\right\}\right]. \qquad (28)$$

From Eq. (28), we can know that the position of the CFP is dependent only on the secondary mirror characteristics. In a classical Cassegrain telescope ($b_{s2,\mathrm{cl}} = -(\frac{m_2-1}{m_2+1})^2$), the CFP is located at the prime focus. In an RC telescope ($b_{s2,\mathrm{RC}} = -[(\frac{m_2-1}{m_2+1})^2 + \frac{2f'}{d_1(m_2+1)^3}]$), the CFP is located between the secondary mirror vertex and the prime focus.

This result is identical to the one derived by Wilson using the Schiefspiegler approach. In general, the position of the CFP is of great importance in the design of systems for active correction of decentering coma [4].

In the general case, $\vec{\sigma}_2^o$ and $\vec{\sigma}_2^*$ due to misalignment perturbations of secondary mirror are noncollinear and Eq. (25) must be combined by vector addition. Equation (25) can also be reduced to coincide with the result solved by Wilson. The reduction will use treatment in which decenter of the spherical surface is equivalent to tilt; as a result, a spherical surface does not have a unique vertex. Here we do not give more representation.

4. Summary

It is common practice to align two-mirror telescopes by tilting and/or decentering the secondary mirror until the coma is removed. In this paper, we explore the coma correction in a fully quantitative form. Derived by a vector approach, the coma-free condition to remove the misalignment-induced coma is presented. The analytic description presented in Section 2 reveals how third-order coma is induced in misaligned two-mirror telescopes. If necessary, the third-order astigmatic field can also be calculated with this approach [6].

The conclusions in this work can be applied to design unobscured reflective telescopes, where there always are decentered and/or tilted elements. We will do this work in the future.

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