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A unique astigmatic nodal property in misaligned Ritchey-Chrétien telescopes with misalignment coma removed

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Abstract: We present the aberration field response of Ritchey-Chrétien telescopes, with the aperture stop on the primary mirror, to secondary mirror misalignments. More specifically, we derive a general condition for the geometry of the binodal astigmatic aberration field for a telescope that has been aligned to remove field-constant coma. It has been observed that when the coma caused by secondary mirror misalignments is removed the astigmatic field is typically not symmetric around the periphery, but, significantly, it is always effectively zero on-axis. This observation is a manifestation of binodal astigmatism where one of the astigmatic nodes remains near the field center. Here, we show how the condition to remove field-constant coma simultaneously creates a constraint whereby one of the astigmatic nodes must remain effectively on-axis. This result points to why the alignment of a large telescope based on axial imagery is insufficient and demonstrates exactly the geometry of the remaining misalignment aberration field, which dominates the performance of the telescope, providing insights into more complete alignment approaches.

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1. Introduction

An aberration theory for optical imaging systems without symmetry, but with rotationally symmetric components, has been developed by Thompson in the 1970s. The work is based on the wave aberration theory of Hopkins [1], the concept of shifted aberration field centers attributed to Buchroeder [2], and a key insight from Shack [3] that the intrinsic geometry for the field dependence of the traditional aberration fields becomes multinodal in the absence of system symmetry. Remarkably, it has been shown that no new wave aberration types emerge in the presence of tilted and/or decentered rotationally symmetric parent surfaces even when the offsets are large, as frequently encountered in unobscured multiple mirror systems. What does happen is that the well known aberrations of rotationally symmetric optical systems can, and particularly in the case of 3rd order astigmatism, do, develop multinodal behavior over the field of view (FOV) with aberration type intrinsic symmetries that have been derived by Thompson [4–6] through fifth order. This multinodal behavior arises directly from the vector summation of the individual surface aberration fields, now accounting for the fact that for each surface, the centers of rotational symmetry of the associated aberration fields are at different locations in the image field [4,7].

Historically, until relatively recently, astronomers have been aligning large telescopes on-site on the basis of removing the appearance of image asymmetry on-axis or with the equally effective technique of centering the obscuration shadow in a slightly defocused on-axis image. More specifically, the tilt or the decenter of the secondary mirror is adjusted until the on-axis image is coma-free. Since coma depends on aperture-cubed it is readily seen as asymmetry in an astronomical image. Alternatively, coma can be measured with wavefront sensing techniques that are deployed on-site to identify the aberrations of the wavefront, often in terms of Zernike coefficients, which are readily converted to the wave aberration coefficients to be used here. Prior to the present decade, most deployed professional astronomical telescopes have been two-mirror designs and in the last 70 years many have been Ritchey-Chrétien (RC) telescopes.

McLeod [8] and others [9–11] have recognized that in fact an alignment method based exclusively on axial imagery is not sufficient to ensure alignment. They report methods for achieving full alignment in the case of rotationally symmetric mirrors, whereby both the tilts and decenters of the secondary mirror are controlled to both eliminate on-axis degradation and also equalize the performance (3rd order astigmatism) around the periphery of the field of view to be unchanged in magnitude and orientation compared to astigmatism of the aligned telescope. More specifically, there is a fixed external pivot point (i.e. away from the secondary mirror vertex, but located on the optical axis of the primary mirror) that the secondary mirror can be rotated about that will affect the astigmatic field but will not result in the introduction of coma into the optical system. Other types of secondary mirror misalignment perturbations will induce field-constant coma, thus including the presence of coma on-axis. Under the conditions where field-constant coma has been removed through secondary mirror alignment, McLeod [8] describes the variation in astigmatism around the periphery of the field of view. A recent paper by the authors, to appear in Applied Optics [12], put the findings of McLeod [8] in the context of Nodal Aberration Theory and in doing so provides a common framework to plan the alignment of observatory-class, two-mirror telescopes built dominantly during the 20th century. Significantly, the Applied Optics work provides a foundation for the current generation of more than two-mirror telescopes, like the Large Synoptic Survey Telescope, where in-fact, an understanding of the nodal properties of higher order aberration fields is significant in the alignment process. It was as part of [12] that the unique nodal behavior now explained here, was discovered through an example. A discussion of field-astigmatism in misaligned two-mirror telescopes has also been given by Wilson [9] and more recently in a detailed paper by Noethe and Guisard [10], who showed that for the specific case of a misaligned Cassegrain telescope that has been aligned to obtain
zero misalignment induced coma, the on-axis point is free of astigmatism. Also, Noethe and Guisard postulated that the conclusions arrived at for Cassegrain telescopes should be approximately valid for RC telescopes.

This paper illustrates, using nodal aberration theory, why the alignment of a RC telescope (stop at primary mirror) to remove field-constant coma also results in the removal of axial astigmatism, even though the astigmatic field varies around the periphery of the field. In this context, the term field center or on-axis refers to the intersection point of a ray that is parallel to the primary mirror optical axis with the detector. In general, in the presence of secondary mirror misalignments, the intersection point differs from the primary mirror optical axis intersection point with the image plane. This result of having one astigmatic node located very close to the field center is an important special case of misalignment aberration fields of astronomical telescopes, which has significant consequences in the development of alignment plans. Specifically, this result illustrates that wavefront sensors placed on-axis will not reveal residual component misalignments.

2. A complete description of the aberration fields of a Ritchey-Chrétien telescope in an arbitrary state of misalignment

As developed by Thompson [5], the aberration field of a RC telescope (neglecting field curvature) with ideal, rotationally symmetric mirrors, with the correct spacing, but in any state of misalignment with respect to tilts and decenters, can be written as

\[ W_{KOSTM, RC} = (-A_{311} \rho)(\rho \cdot \rho) + \frac{1}{2} W_{222}[(H - a_{222})^2 + b_{222}^2] \cdot \rho^2. \]  

(1)

The first term is a description of misalignment induced coma, which is an aberration field that is constant everywhere in the field. \( A_{311} \) is an unnormalized vector that characterizes the magnitude and the orientation of misalignment induced field-constant coma, to be detailed in Section 3, and whose magnitude is linearly proportional to the tilts and decenters of the secondary mirror optical axis with respect to the primary mirror optical axis. The second term is a representation of binodal astigmatism. Here, \( W_{222} \neq 0 \) is the total wave aberration for astigmatism in the telescope, \( H \) is a normalized vector denoting the particular field point where the magnitude and orientation of the astigmatism is being evaluated, \( \rho = \rho(\sin(\phi), \cos(\phi)) \) denotes a normalized vector that points to a position in the exit-pupil, \( a_{222} \) is a normalized vector from the intercept of the Optical Axis Ray (OAR) [5] with the image plane to the midpoint between the two astigmatic nodes to be discussed in Section 4, and \( b_{222}^2 \) is a normalized squared vector that can be decomposed into two anti-parallel vectors from the endpoint of the \( a_{222} \) vector to the two astigmatic nodes as derived and described in [3,5], which is also further detailed in Section 4.

3. Nodal constraints of a coma-aligned Ritchey-Chrétien telescope

On an operational observatory site, on installation, on recoating, and, depending on the facility, periodically in between, the alignment of the telescope is tuned up such that the optical axis of the secondary mirror is adjusted to directly overlap that of the primary mirror. In the case where only axial imagery is used, this operation essentially sets the \( A_{311} \) term to zero by adjusting either the tip-tilt or the decenter of the secondary mirror. The \( A_{311} \) term for a RC telescope with the aperture stop at the primary mirror is given by

\[ A_{311} = W_{131,PM}^{( sph)} + W_{131,SM}^{( sph)} + W_{131,SM}^{( asph)}, \]  

(2)

\[ W_{131} = W_{131,PM}^{( sph)} + W_{131,SM}^{( sph)} + W_{131,SM}^{( asph)} = 0, \]  

(3)
where $\sigma_{SM}^{sph}$ denotes the contribution to the aberration fields of a conic mirror originating from the spherical base surface, which is typically dominated by secondary mirror tip-tilts, $\sigma_{SM}^{asph}$ corresponds to the aberration field associated with the conic/aspheric departure from the base sphere, which is affected by decenter, $\theta_{PM}$ denotes the chief ray angle in object space, $c_{SM}$ corresponds to the curvature of the secondary mirror, $d_i$ denotes the mirror separation, and $XDE_{SM}$, $YDE_{SM}$ and $BDE_{SM}$, $ADE_{SM}$ denote the decenter and tip-tilts of the secondary mirror in the two planes ($x$ and $y$), respectively, where the $z$ – direction coincides with the primary mirror optical axis.

Equations (4) and 5 were derived using the expressions for the aberration field centers provided in [7] combined with general raytracing of the OAR through the tilted and decentered telescope, utilizing the primary mirror (coincident with the stop) as coordinate reference. These equations were also validated using optical design software. Expressions for aberration field centers assuming different pupil locations can be obtained similarly, but are not included here, since the specific nodal property of having one astigmatic node close to the field center is a special case for the pupil location at the primary mirror and is not necessarily the case for other stop configurations.

Figure 1(a) shows the surface-by-surface distribution of individual mirror wave aberration coefficients for coma and astigmatism, including a separation of the base sphere and aspheric/conic contributions for a typical RC telescope (stop at primary mirror), fully described by an EPD of 3 m, an EFL of 32 m, a linear obstruction of 0.31, a secondary mirror magnification of $-4.25$, and a maximum field of 5.94 arcmin. It is important to note that both coma contributions (spherical and conic/aspheric) of the secondary mirror are of the same sign. This is a general condition of a RC telescope (with the stop at the primary mirror) as the terms are working to cancel the intrinsically larger contribution from the primary mirror. In contrary, considering the signs for the secondary mirror spherical and aspheric contributions of astigmatism, it is observed that the signs are opposite, which will be important for the constraint on the astigmatic node locations discussed in Section 4. Apart from the trivial case of perfect secondary mirror misalignments ($\sigma_{SM}^{sph} = \sigma_{SM}^{asph} = 0$), the two $\sigma_{SM}$ vectors must point into opposite directions when requiring zero misalignment induced constant coma, i.e. $A_{11} = 0$, given the identical signs and similar magnitudes of $W_{111,SM}^{sph}$ and $W_{111,SM}^{asph}$.

Figure 1(b) illustrates the constraint on the spherical and aspheric aberration field center vectors when requiring zero misalignment induced constant coma. For a typical set of secondary mirror misalignments [listed in Fig. 1(b)], the aberration field center vectors $\sigma_{111}^{sph}$ and $\sigma_{111}^{asph}$ are visualized, where the * refers to the initial misalignments before the compensation of misalignment induced coma. In this case, a tip-tilt to the secondary mirror was applied to cancel constant coma, leading to a new vector pointing to the center of the aberration field due to the base sphere of the secondary denoted by $\sigma_{bas}^{sph}$. As shown in Fig. 1(b), the applied tip-tilt to the secondary mirror only modified the $\sigma_{bas}^{asph}$ vector, which now points in exactly opposite direction to the aspheric aberration field vector. The aspheric aberration field center vector remains unaffected ($\sigma_{bas}^{sph} = \sigma_{bas}^{asph} = 0$), since a tip-tilt of the secondary mirror does not change the location of the secondary mirror vertex. In general there are any number of combinations of tilt and decenter of the secondary mirror that effectively rotate the secondary mirror about a fixed point on the optical axis of the primary mirror that will result in the cancellation of constant coma.
Fig. 1. (a) The surface-by-surface wave aberration coefficients for coma and astigmatism of a typical RC telescope including the separation of the contribution from the spherical base curve of a conic/aspheric mirror and the contribution from the conic/aspheric departure. (b) Aberration field center vectors for the spherical base curve and conic/aspheric contributions of the secondary mirror of a misaligned RC telescope. The opposing alignment of $\sigma_{SM}^{(sph)}$ and $\sigma_{SM}^{(asph)}$ is a key constraint imposed by the correction of misalignment induced coma.

4. Misalignment induced binodal 3rd-order astigmatic aberration field in a Ritchey-Chrétien telescope

Returning to Eq. (1), the second nodal vector for astigmatism, $b_{222}^2$, is defined [3,5] as,

$$b_{222}^2 = \frac{B_{222}^2}{W_{222}} - a_{222}^2,$$

with, for a RC telescope with the aperture at the primary mirror,

$$B_{222}^2 = W_{222,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{222,SM}^{(asph)} \sigma_{SM}^{(asph)},$$

$$a_{222} = \frac{A_{222}}{W_{222}} = \frac{1}{W_{222}} \left( W_{222,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{222,SM}^{(asph)} \sigma_{SM}^{(asph)} \right).$$

In investigating this model, a general result was discovered that cannot be easily seen from the original work, but, is in-fact a useful general insight for the form of the misalignment induced astigmatic field of a RC telescope with the stop at the primary mirror. In the original work, the nodes for astigmatism are generally found from solving the second term in Eq. (1) for $H$ as

$$W_{AST} = \frac{1}{2} W_{222} \left[ (H - a_{222})^2 + b_{222}^2 \right] \rho^2 = 0,$$

$$\rho^2 = 0,$$

$$H = a_{222} \pm b_{222},$$

Graphically, as shown in [3,5], the operation of taking the square root of a negative vector, $-b_{222}^2$, results in a rotation of the $b_{222}$ vector by $\pm 90^\circ$ before it is added to $a_{222}$. This operation does not result in any general constraint on either of the astigmatic node locations.

In the case of a RC telescope that has been aligned to remove field-constant coma, one can make an important general conclusion that does provide a constraint on one of the two astigmatic nodes. To recognize the intrinsic astigmatic nodal behavior of a coma-aligned RC telescope, one needs to look at the interaction of the components of $A_{222}$, $a_{222}$, and $b_{222}$, knowing now that requiring zero field-constant coma ($A_{31} = 0$) results in the constraint
that the two $\sigma$-vectors for the secondary mirror aberration field centers must take on opposite directions. With this new knowledge, consider the implications for $b_{222}^2$ and more specifically the components of $B_{222}^2$ given by Eq. (7). As presented in Appendix A of [5], a squared vector is the same vector whether the component vector is considered positive or negative. From Fig. 1(a), the components for the two wave aberration coefficients for the secondary mirror for astigmatism are of opposite sign, which is in fact a general property of RC telescopes. They are also of similar magnitude assuming a typical location of the image plane behind the primary mirror, a secondary mirror magnification between $-6$ and $-2$, and an obscuration ratio within 0.15 to 0.35. Therefore, for any practical RC telescope with the aperture stop on the primary mirror $B_{222}^2 \ll a_{222}^2$, and, as a general result, 

$$b_{222}^2 \equiv (-a_{222}^2).$$

(10)

Now, revisiting Eq. (9), with this new result, for a coma-aligned telescope,

$$H - a_{222} \equiv -b_{222}^2 \equiv -(-a_{222}^2) \equiv a_{222}^2,$$

(11)

$$H = a_{222}^2 \pm a_{222} \equiv 0, 2a_{222}.$$

This is a general result that describes the most common state of alignment for a RC telescope that has been aligned to remove field-constant coma, but has not been aligned based on the periphery of the field. As demonstrated, aligning the telescope for zero field-constant coma removes all axial wavefront aberration, but it does not put any constraints on image quality degradation at the edge of the field of view, which is illustrated in Fig. 2. Specifically, Fig. 2(a) compares the astigmatism in the case of rotational symmetry with binodal astigmatism after aligning the telescope for zero field-constant coma [Fig. 2(b)].

5. Conclusion

We have presented a significant insight into the misalignment induced aberration fields of Ritchey-Chrétien telescopes with the aperture stop at the primary mirror that can be attributed to the application of nodal aberration theory. It has been shown that having one of the nodes of binodal astigmatism essentially at the field center of the telescope is not coincidental; it is a necessary consequence of removing misalignment induced coma. Having described the reason for the occurrence of the astigmatic node at the field center, this finding emphasizes the importance of measuring astigmatism at off-axis field points to assess the alignment state of the telescope. This particular nodal property of misalignment induced binodal astigmatism will be combined in future work with the effects of astigmatic figure errors on the astigmatic aberration field, which can be utilized to distinguish astigmatism caused by mirror misalignments and figure errors.
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