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Research Article

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The astigmatic aberration field in active primary mirror astronomical telescopes

Abstract: Stemming from the exceptional results obtained with the pathfinding NTT telescope commissioned in 1989, the current generation of large astronomical telescopes, including the VLT, Gemini, Subaru, LBT, VST, and many more, use an active primary mirror in conjunction with the position of the secondary mirror to optimize performance with a cycle time typically measured in minutes over the course of acquiring a long exposure image. Recent discoveries, based in research enabled by the nodal aberration theory (NAT), have created a complete, linear model for the effect of, and the interaction of, the alignment compensators used during an exposure when an active primary mirror has a role in the process of maintaining performance in combination with the rotation of the secondary mirror around a specific external pivot point. This scenario, presented in the context of NAT, clearly illustrates important, limiting interactions between the secondary mirror position and the primary mirror astigmatic figure residual created through active control. It also points to the need for the wavefront sensor algorithm to anticipate that the astigmatic field will be binodal. The science of weak galactic lensing is exceptionally sensitive to binodal astigmatism, making this aberration field an urgent area of research.

Keywords: aberration fields; active primary mirror; astigmatism; misaligned telescopes; nodal aberration theory; telescope alignment.

OCIS codes: 220.1000; 220.1140; 220.1080; 350.1260.

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1 Introduction

The current generation of large, ground-based astronomical telescopes have adopted, in general, an alignment process in advance of and often during an exposure that involves pivoting the secondary mirror about an external pivot point (on the optical axis, but away from the vertex) and an active primary mirror with wavefront sensor-driven updates on a duty cycle of the order of 1 min. The control of the primary mirror figure during exposure is directed by typically a single wavefront sensor that is placed just beyond the science field of view. The position of the secondary mirror is typically set in advance of an extended exposure to result in a boresight control and the removable of the axial coma. In the case of the emerging generation of the wide field-of-view survey telescopes, like the VST, refractive lenses are placed near the focal plane to extend the field of view. It is significant to note that the two-mirror telescope optical design for these wide-field systems, without the field extending refractive lenses, is not corrected for either coma or astigmatism; this role is delegated to the refractive lens group. In the case of the VST, the wavefront sensor pickoff mirror is located ahead of these corrective lenses. As a result, the nominal telescope aberration field at the wavefront sensor that controls the primary mirror figure is not sampling a corrected image; rather, the wavefront sensor is analyzing an image with significant coma and astigmatism (but typically no spherical aberration). It is important then to understand what specific features the comatic and astigmatic field dependence develops in the presence of both misalignment of the secondary mirror and in the presence of deliberately introduced astigmatic figure on the active primary mirror.

The purpose of this paper is to present the recent findings based in nodal aberration theory (NAT) on the structure of the astigmatic aberration field presented to the wavefront sensor and the response of that aberration field to the deterministic adjustments to the primary mirror figure. This paper will focus on the astigmatic field because it is this aberration that will dominate the degradation of the telescope imagery in the science mode. This fact, that the astigmatic field will dominate performance, is a critical feature in the science of weak lensing [1]. The comatic field, in this application, is readily maintained in a nearly ideal state with the position of the secondary mirror, as is the spherical aberration. The next aberration that emerges to dominate in the series is astigmatism. Following the successful control of the astigmatic field, trefoil and quadrafoil residuals due to the actuators on the primary mirror are the next sources of performance degradation.

This work is based on the wave aberration theory of Hopkins [2], the concept of shifted aberration field centers attributed to Buchroeder [3], and a key insight from Shack [4] that combined led to the discovery by Shack that the astigmatic aberration field in the two-mirror astronomical telescopes becomes binodal when the symmetry is broken caused by either secondary misalignment or primary mirror figure error (i.e., there are two points in the star field that clearly display no astigmatism). This behavior, which was first observed on Kitt Peak in 1976, is shown in a through-focus star plate that is included in [5]. Until recently, the NAT, discovered by Shack [4] and developed by the author [5], has been limited to optical imaging systems made of rotationally symmetric components, or offset aperture portions thereof, that are tilted and/or decentered. Recently, the special case of an astigmatic optical surface located at the aperture stop (or pupil) (e.g., telescope primary mirror) was introduced into the NAT by Schmid et al. [6] and analyzed for the case of a primary mirror in a two-mirror astronomical telescope. This work is directly relevant to the active primary mirror implementation that has become a baseline in modern ground-based telescopes. Most recently, Fuerschbach et al. [7] described a significant extension to NAT that encompasses the most general case, surface deformations (represented by terms 4–16 in the FRINGE Zernike set, and beyond) that are applied to the surfaces that are not at the stop/pupil. This extension has enabled, for the first time, an understanding of the response of the astigmatic aberration field in a telescope with a three-point mount-induced error (trefoil) on the secondary mirror. It is significant to note that one very important discovery is that the mount-induced trefoil aberration on the secondary mirror creates an analytic multinodal response in the astigmatic field. These results provide a basis for creating a simple, linear model for the interaction of the hexapod-based secondary mirror alignment with the active figure control on the primary of a VST-like telescope. For readers not familiar with the NAT, Ref. [5] is recommended as a starting point.

The key new concept that is understood from NAT is that the traditional aberration fields that limit the performance of the current generation of two-mirror telescopes including spherical aberration, coma, field curvature, and astigmatism develop specific responses to tilts and decenters that are analytically predicted by NAT and verified by real ray traces based in Zernike decompositions of the wavefront over a dense grid of field points. Most dramatic is the discovery that, in the case of astigmatism, the quadratic field dependence of an aligned telescope develops in all cases a binodal field dependence during the alignment process and in the presence of a primary mirror active figure control. Significantly, we have found specific rules that govern particularly the emergent binodal astigmatism both in the context of secondary mirror alignment and in the context of primary mirror astigmatic figure. These rules clearly distinguish the cases of secondary misalignment from the case of primary mirror astigmatic figure and allow decoupling these effects in a linear metric space when they coexist, which is, in fact, the most common case with the current generation of large telescopes with active primary mirrors.

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 (third-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 binodal astigmatic field but will not result in the introduction of axial coma into the optical system. Under the conditions where axial coma has been removed through secondary mirror alignment, McLeod [8] describes the variation in astigmatism around the periphery of the field of view. A discussion of field astigmatism in misaligned two-mirror telescopes has been given by Wilson [9] and more, recently, in a detailed paper by Noethe and Guisard [9], 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 Ritchey-Chrétien telescopes. Using the NAT confirmed with real ray trace data, Schmid et al. [12] confirmed the postulate of Noethe and Guisard and provided a comprehensive linear model of the interaction of the dominant aberration fields with the alignment states of Cassegrain, Ritchey-Chrétien, and even the three mirror anastigmats (TMAs) (e.g., the James Webb Space Telescope). Finally, Sebag et al. [13] described the use of NAT in planning the fabrication, testing, and alignment of the Large Synoptic Survey Telescope (LSST).

2 Applying nodal aberration theory to a VST-like telescope at the wavefront sensor

To illustrate the high-level insights that can be extracted from the NAT in the context of the operation of a large astronomical telescope with an active primary mirror, a VST-like telescope, shown in Figure 1, will be used here based on an optical design prescription that was found on the Internet [14]. Figure 2 provides two types of displays of the magnitude and separately the magnitude and orientation of the coma aberration field and of the astigmatic aberration field for the telescope shown in Figure 1 in a perfect alignment state. Here, the third-order coma field depends linearly on the field of view, while the astigmatic field depends quadratically on the field of view, a well-established third-order aberration theory result. Throughout this paper, the 3D color plots are based on the NAT, an analytic, predictive theory. The 2D plots of the magnitude and orientation of an individual are based on performing a Zernike decomposition of real-ray wavefront data computed on a dense grid of field points. For this class of telescope, the Zernike aberration terms, which are not typically associated with a field dependence, are essentially identical to the conventional third-order Seidel aberrations. The extension of the Zernike coefficients to include field dependence is described by Gray et al. in [15].

2.1 NAT insights applied to the comatic aberration field at the wavefront sensor

It is well-known in the astronomy community that the presence of axial coma (i.e., on-axis coma) is a direct

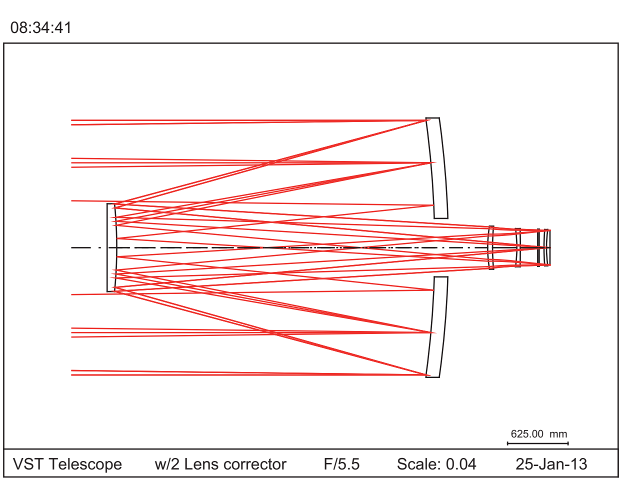

Figure 1 A VST-like telescope with refractive field extender [14].

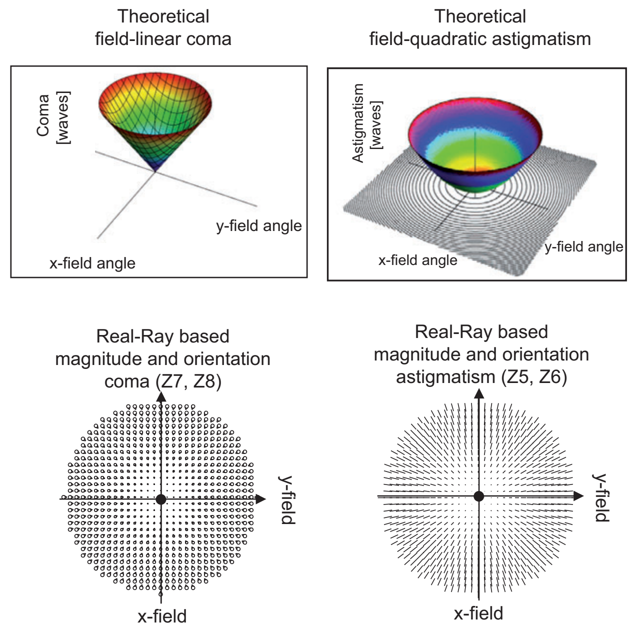

Figure 2 The field-linear coma aberration field in an aligned VST-like telescope (left) and the field-quadratic astigmatic aberration field in an aligned VST-like telescope (right). The lower plots are real ray-based full-field aberration displays (FFD) for the VST-like telescope shown in Figure 1, [12]. Here, the size and orientation of the plot symbol is produced based on a FRINGE Zernike decomposition of the wavefront at each sampled field point.

indication that the telescope is misaligned, more specifically that the displacement of the secondary mirror is not described by a rotation about a coma-neutral point somewhere on the primary mirror optical axis. The optical axis of the primary mirror is, by definition, the line that connects the center of curvature of the primary mirror with the center of rotational symmetry of the conic departure of the as-fabricated primary mirror. What is less well-known is that when axial coma is measured on-axis, there remains a location, typically within the telescope field of view, with no coma. What is also just becoming generally known is that the correction of axial coma, which ensures no axial astigmatism (with an ideal primary mirror), in no way ensures the telescope is aligned. In fact, the data at the periphery of the field is needed to confirm alignment. This is shown in Figure 3.

Based on the documentation available on the Internet [16], the VST telescope is prealigned using the secondary mirror position in both the tilt and decenter based on two different preplanned external pivot points implemented using a hexapod mount. The order is to first place the point of zero coma onto what has been mechanically defined as 'on-axis' pivoting around the center of curvature of the secondary mirror (thereby, not affecting the optical boresight). Then, the boresight is brought to the same point,

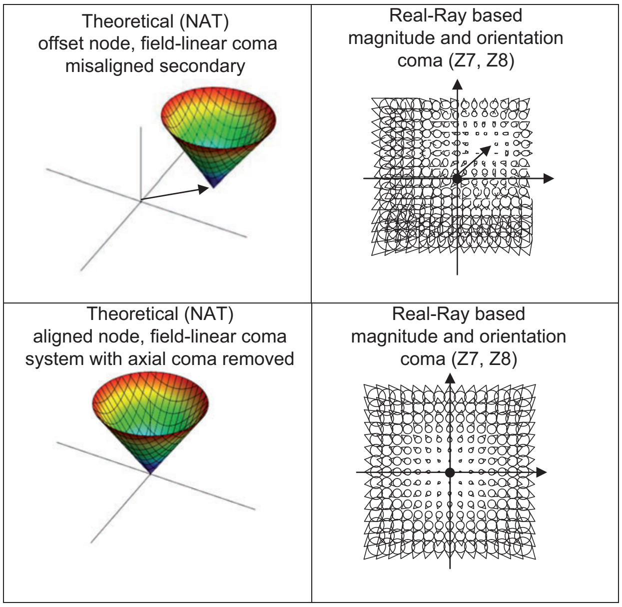

Figure 3 The dominantly third-order, field-linear comatic aberration field in a misaligned (top) and aligned (lower) VST-like two-mirror astronomical telescope. The measurement of axial coma in a telescope that has as a design residual third-order field-linear coma simply indicates that the field point with zero coma (the coma node) is no longer on-axis [5]. Combinations of tilt and decenter of the secondary mirror are used in alignment to return the coma node to the center of the field of view as illustrated in the lower plots [12].

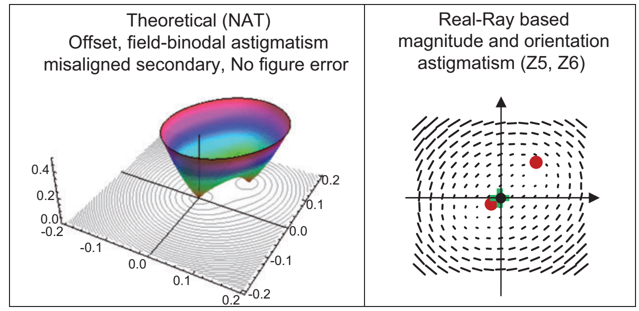

Figure 4 The most common binodal astigmatic field in a two-mirror telescope aligned for zero axial coma. The zero axial coma constraint also ensures zero axial astigmatism; however, if only axial information is used, the most likely astigmatic field is binodal of the form shown here [12, 17].

by pivoting the secondary about the coma-free pivot point. By adjusting the secondary about the external pivot located at its center of curvature, the boresight is unaffected (i.e., a 'pointing-free coma adjustment'). In fact, using insights from the NAT, this method, which fixes the location of the secondary mirror center of curvature, effectively uses the decenter of the secondary mirror conic contribution to the overall coma field to move the coma field zero to align with a reference point on the focal plane. The second alignment is based on adjusting the commands to the hexapod such that the external pivot point is now located at the coma-free pivot, a point where the contribution due to the decenter of the secondary mirror center of curvature exactly balances the contribution due to the vertex decenter of the conic departure.

As shown by the NAT, and independently by McLeod, the alignment of the telescope based on the removal of the axial coma is not sufficient to ensure telescope alignment. There is a continuous combination of secondary tilt and decenter about the readily computed external pivot point that maintains zero axial coma. While boresight does change with this adjustment, boresight on its own is not a good constraint, as boresight errors can arise from a variety of non-optical causes, such as mount pointing errors. What is essential to realize, and a key recent result from NAT, is that when the telescope is aligned for zero axial coma, it will also, in any practical case, display no axial astigmatism [17]. However, and a key motivation for this paper, there will be a strongly binodal astigmatic field. Figure 4 illustrates the most common form of binodal astigmatic field in a two-mirror telescope, where the secondary mirror is aligned based on removing axial coma. The key feature, which is readily extracted from NAT, is that one of the two astigmatic nodes will always remain essentially on-axis, confirming the postulate of Noethe and Guisard in [10], as will the comatic field node, but the other node will not be effectively constrained by the alignment process outlined to this point. Under these conditions, the magnitude of the astigmatism at any point in the field is proportional to the product of the linear distance in the field to each of the nodes individually. For systems where the second node has moved well beyond the observing field, this magnitude can appear to be linear within the observing field, but, significantly, the orientation of the astigmatic images is not radially symmetric about the center of the field as illustrated in Figure 4 of [18]. The presence of residual binodal astigmatism appears to be a very common state of alignment for many large astronomical telescopes currently and is particularly troubling for any telescopes in use for categorizing elliptical galaxies.

2.2 NAT insights applied to the binodal astigmatic aberration field

An innovative feature in many of the new family of astronomical telescopes, first developed in Europe, is the decision to use thin primary mirrors combined with a relatively sparse set of actuators that send corrections on a duty cycle of the order of a minute during long exposures based on information supplied by a Hartmann-Shack wavefront sensor operating just beyond the science field of view and with a pickoff just ahead of the refractive field widening lenses. In the context of this paper, the actuators introduce astigmatic corrective figure on the primary mirror with the goal of creating the anticipated magnitude and orientation of the astigmatic image on the wavefront sensor for the field point being sampled (i.e., field-quadratic astigmatism centered on the telescope optical axis). However, and a main purpose of this paper, if the corrective algorithm does not anticipate that the astigmatic field is binodal, which it is in all cases other than perfect alignment, the ability to close on an aligned telescope is compromised. Figure 5 illustrates the response of the astigmatic field to the introduction of astigmatic figure on the primary mirror. The theory that supports the real ray-based results shown in Figure 5 is provided by Schmid et al. in [6].

For a two-mirror telescope in the VST class that is an essentially Cassegrain form (when not considering its field widening lenses), only spherical aberration is corrected and not the field linear coma or field quadratic astigmatism. With this set of dominant aberration fields, binodal astigmatic field response to secondary misalignment always takes the form shown in Figure 4; one node always remains essentially on-axis. Independently, the binodal astigmatic field response to primary mirror astigmatic figure introduced by the actuators in response to the input from the wavefront sensor always takes the form shown in Figure 5; both nodes emerge and expand away from on-axis equally. With this insight, one can quickly conclude that during an exposure, if only the primary figure is being actively controlled, and not the secondary mirror position (which is the case described in the early VST documents), then, any change in the secondary mirror position due to gravity over the exposure time cannot, in fact, be effectively negated by the primary mirror.

More significant than decoupling the performance compensation during exposure provided by the secondary mirror position and the primary mirror figure during exposure, the aberration field anticipated by the wavefront sensor needs to assume that the astigmatic field will be binodal. For an off-axis wavefront sensor, if the wavefront decomposition algorithm does not anticipate a binodal astigmatic field, then it cannot possibly provide a successful instruction set to the primary mirror astigmatic figure controller, and in fact will, in general, be sending unhelpful amounts of astigmatic overcorrection or undercorrection to the science field. Under the condition that the wavefront sensor correction algorithm is not configured to understand the binodal astigmatic fields, Figure 6 shows the status of the telescope. The on-axis coma is maintained by the combined location of the tilt and decenter of the secondary, but the secondary is not typically aligned to the primary mirror in an astigmatic context, and the primary mirror figure actuators are introducing an astigmatic figure residual in an attempt to satisfy the incomplete conditions that are the wavefront sensor algorithm.

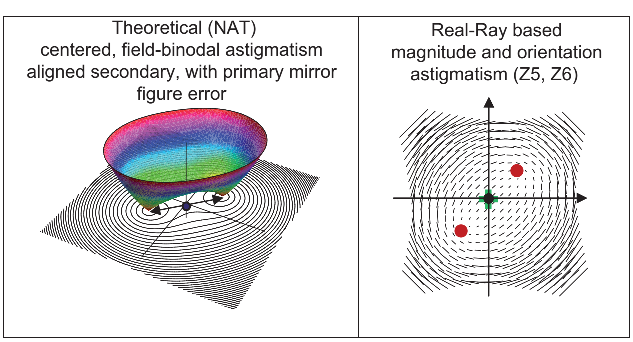

Figure 5 The binodal astigmatic field for a perfectly aligned two-mirror astronomical telescope with residual astigmatic figure error on the active primary mirror. Here, the two astigmatic nodes develop symmetrically about the center of the field and the on-axis astigmatism results. The astigmatic primary mirror figure error only affects the spacing between the two nodes [6, 12].

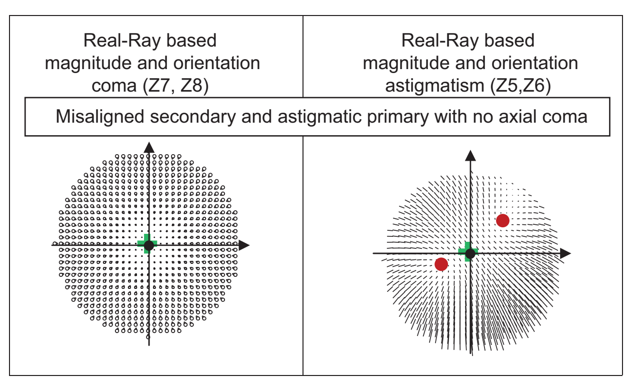

Figure 6 The most likely state of aberration field structure during the operation of large astronomical telescopes with thin primary mirrors whose astigmatic actuators are driven by a single wavefront sensor located just outside of the science field of view. Note that coma is zero at the on-axis point, but the real ray-based Zernike displays shown here include the effects of all order of aberration within the comatic type (see [15]), as a result, there is a very weak asymmetry across the full format due to the higher-order nodal effects that are presented in detail in [19].

3 Corrective actions suggested by NAT for VST-like large astronomical telescopes with thin, active primary mirrors

The application of NAT to VST-like telescopes provides a clear path to understanding the interaction of the position of the secondary mirror in tilt and decenter and the effects of the primary mirror actuators on the astigmatic field in a completely linear space. For both comatic and astigmatic third-order aberration fields, which dominate the performance of this class of telescope, the nodal positions are linearly related to the tilt and decenter of the secondary and to the astigmatic figure error applied to the primary mirror. To improve both the rate of closure on alignment in real time and the resulting residual alignment-induced degradation that compromises the performance of these otherwise state-of-the-art telescopes, it is sufficient to look to upgrading the wavefront sensor algorithm that provides the corrective signal to the primary mirror. It is possible, knowing the telescope parameters and the boresight condition independently to reconstruct the location of the two astigmatic nodes from a single wavefront measurement made near the edge of the field. Figure 7 shows the data available to the wavefront sensor for both a misaligned and an aligned state. Without knowledge that the misaligned telescope displays a binodal astigmatic field, it is not possible to effectively interpret the information presented to the wavefront sensor, which would only sample one or a few of the field points shown in the acquisition ring. There is some degeneracy and increased noise sensitivity in this approach, and having a second measurement is the best approach to get the best characterization of the status of the astigmatic field at any specific time.

4 Conclusions

This paper has pointed to the application of insights from the NAT to the new generation of large-aperture astronomical telescopes being deployed around the world based on the technology of a deformable primary mirror whose figure is controlled by a relatively sparse set of actuators. Specifically, NAT provides a clear path to understanding the interaction of the alignment of the secondary mirror with the astigmatic figure error that can be deliberately introduced onto the primary mirror based on image quality information obtained just outside of the science field of view. Perhaps more significant, the NAT insights point to interactions that are each linear in the misalignments and in the applied figure error.

An outcome of these insights points to a path to improve the real-time image quality of these thin primary mirror telescopes during long exposures. By upgrading the wavefront sensor algorithms to acknowledge that the typical astigmatic field will be binodal, the closure to achieve optimal alignment in real-time can be improved

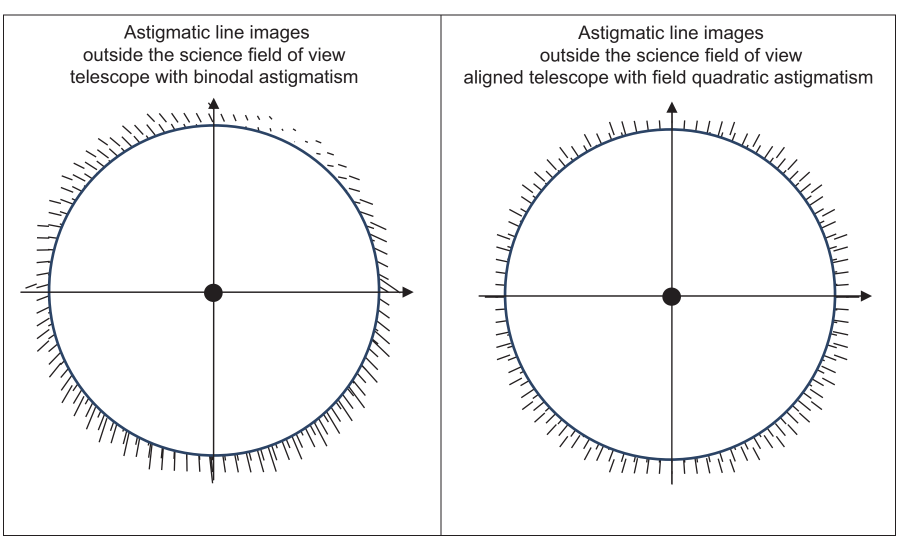

Figure 7 Comparing the astigmatic aberration field in the sample zone of the wavefront sensor for the aligned and the misaligned VST-like telescope. Note that the information available on the left (misaligned) is not interpretable without the knowledge that it is, in fact, a manifestation of a binodal astigmatic field. Note, in particular, the astigmatic features in the upper right quadrant of the left figure.

as can the uncorrected alignment residual. Currently, the science of weak lensing [1] is extremely sensitive to the existence of a binodal astigmatic field.

With proper control of the field linear comatic aberration field and astigmatic field, the next most likely source of telescope degradation is the secondary mirror mount. Typically, the residual aberration field in this case is a trefoil aberration. Recent work by Fuerschbach has unraveled, for the first time, in the context of NAT, the interaction of trefoil on the secondary mirror with the astigmatic field structure. The results, which are truly fascinating, were anticipated in work by the author in 1979 [20], the relevant parts of which are more recently published in [21]. Fuerschbach's discovery is documented in [7], and this work is immediately relevant to the class of actively deformable primary mirror telescopes treated here.

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