Exploring the design space of 3-mirror freeform imagers

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Abstract: Variations on a large aperture three-mirror freeform imager are explored. The tradeoff of optical performance with design parameters such as F-number and FOV aspect ratio is quantified. Reimaging and wide-FOV systems are also studied.
OCIS codes: (080.1010) Aberrations; (080.4225) Nonspherical lens design

1. Introduction

The introduction of freeform optics into an optical system without symmetry has been shown to provide a significant advantage in terms of system volume [1, 2], optical performance [3], increased specifications, or a combination of all three. Three-mirror imagers offer the degrees of freedom necessary to achieve exceptional optical performance and the ability to construct systems with widely varying properties. The reflective triplet [4] can achieve a moderate field-of-view (FOV) while maintaining a compact size; a three-mirror anastigmat [5] has wonderful stray light mitigation properties though cannot operate at the same FOVs as a reflective triplet; and the three-mirror long supports a wide FOV, though the system volume is quite large [6]. These three-mirror forms are shown in Fig. 1. In this work, we apply freeform surfaces to each of these systems to discover the freeform advantage of each form. First, the reflective triplet is explored in the context of a 250 mm aperture, 3° full FOV system. The tradeoffs of optical performance with faster F-numbers and anamorphic FOV aspect ratios are explored. Then, reimaging is introduced and the ideal folding geometry is found and optimized. Finally, the FOV is pushed to the extreme yielding a three-mirror long inspired system with a 125 mm aperture and 25° full FOV. Principles to help choose the ideal folding geometry for the starting design are introduced.

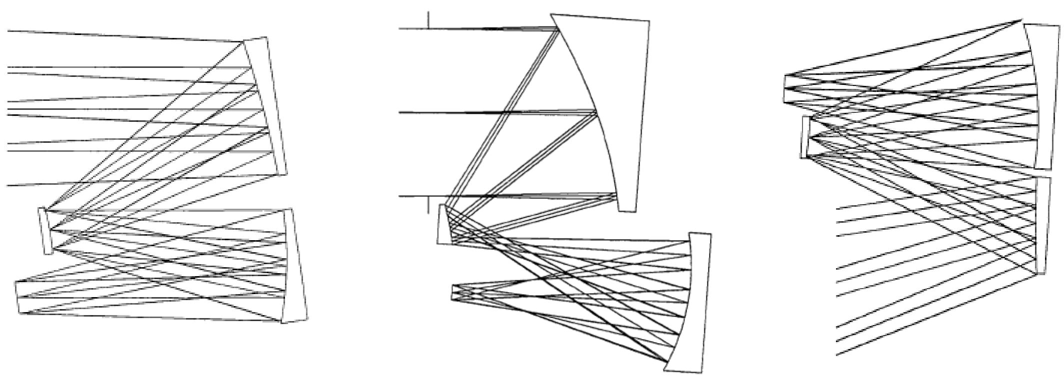

Fig. 1. Design form illustrations of the (left) reflective triplet, (middle) three-mirror anastigmat, and (right) three-mirror long (Adapted from [7]).

2. F-number and aspect ratio study

F-number is typically an indicator of the amount of light entering into the system or system resolution, but in the context of a reflective triplet, we are using F-number as a degree of freedom to find the best balance of performance and system volume. We found that over the range of F-numbers studied that there is an F-number for a given system volume that optimizes the optical performance, and that F-number is not necessarily the slowest option.

In the same design form, we studied the effect that FOV aspect ratio has on the achievable optical performance. The reflective triplet only uses surface tilts in one dimension, so if vertical FOV can be transitioned to horizontal FOV without changing the overall amount of information acquired by the system as shown in Fig. 2, there is an opportunity to decrease the magnitude of the surface tilts necessary for ray clearance and, thus, decrease the magnitude of the asymmetric aberrations. We found that, indeed, there is an optimal aspect ratio for which the optical performance is maximized for a given set of specifications.

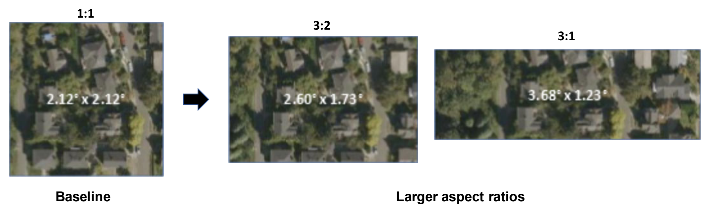

Fig. 2. Trading vertical FOV for horizontal FOV without changing imaged area can result in better optical performance.

3. Reimaging system and ultra-wide FOV design studies

By requiring the system to have an intermediate image and an accessible exit pupil, superior stray light mitigation can be achieved in the reimaging three-mirror imager. However, compared to the reflective triplet, the mirror powers can be almost double, resulting in additional aberrations. Each folding geometry has unique aberration properties and, therefore, it can be either easy or difficult to efficiently implement freeform optics into the system. Similarly, for a system with a wide FOV, the aberration properties of the various folding geometries are unique. As explained in Fuerschbach et al. [8], not all combinations of aberrations can be corrected efficiently. For example, a coma shaped surface adds field-asymmetric, field-linear astigmatism and field-constant coma with a defined relative orientation between the two, as illustrated in Fig. 3. We applied three filters to each folding geometry for the reimaging and ultra-wide FOV systems to predict the freeform correction potential of the folding geometry without the need to optimize the system. The first filter checks the relative orientation between the field-asymmetric, field-linear astigmatism and the field-constant coma so that a single coma shaped surface can be used away from the stop to simultaneously correct both limiting aberrations. The second filter checks that the focal plane tilt is reduced when implementing the correction suggested by the first filter. The third filter verifies that the system can be put into a flat-field solution without requiring significant surface tilt and/or mirror powers. If a folding geometry satisfied all three filters, it can be corrected efficiently using freeform surfaces. If any of the filters are not satisfied, then the most efficient addition of freeform surfaces is not possible, which often leads to excessive freeform departures.

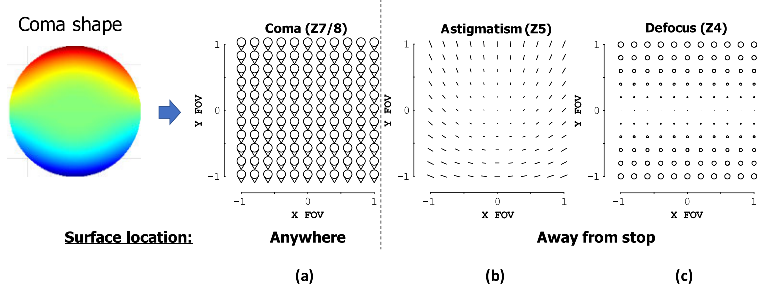

Fig. 3. A freeform surface with the comatic shape as shown will produce (a) field-constant coma, (b) field-asymmetric, field-linear astigmatism, and (c) focal plane tilt with definite relative orientations.

In both cases, the "zig-zag" geometry was shown to be the optimal geometry from an aberration correction standpoint. It passes all three filters for all cases. For this geometry, when compared to a similar system that uses off-axis section of otherwise rotationally symmetric aspheres, there is a 3x improvement in performance or 3.5x improvement in volume for the wide FOV system and a 2x improvement in performance for the reimaging system.

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