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ABSTRACT

We compare the optical performance, alignment sensitivity, and thermal stability of a Non-Uniform Rational B-Spline (NURBS) freeform telescope design to two more conventional design forms with the goal of facilitating acceptance of this new optical surface for aerospace applications. We present the designs of three three-mirror anastigmat (TMA) wide field (4°) telescopes with identical first order optical design parameters. These TMAs consist of a conventional design using off-axis aspheric mirrors, a freeform design using off-axis Zernike polynomial surfaces, and a freeform design using NURBS surfaces. Of the three, the NURBS design gives the best image quality and lowest geometrical design residual. The three designs have similar misalignment sensitivities and sensitivity to thermal soaks, countering a common misconception that freeform designs are more sensitive to misalignment than conventional designs.

Keywords: Freeform, aspherics, NURBS, optical design, TMA, tolerance analysis

1. INTRODUCTION

Ongoing advances in the design, manufacture, and metrology of freeform optical surfaces have led to their proliferation in numerous optical systems. For a given volume and number of optical elements, the added degrees of freedom enabled by freeform surfaces allow improved image quality over a larger field of view (or equivalent image quality in a smaller package). This ability to enhance optical performance while maintaining or reducing telescope volume and number of elements is of particular interest in aerospace applications where size, weight, and power (SWaP) is at a premium.

MIT Lincoln Laboratory has pioneered both the design[1] and fabrication[2] of NURBS freeform optical surfaces for use in imaging systems. Our proprietary optical design software FANO[3] (Fast Accurate NURBS Optimizer) takes an initial non-freeform design file generated from a Zemax model and optimizes the optical surfaces and system geometry to reduce spot size over the field of view[4]. The FANO design code uses a fast raytrace engine designed for NURBS surfaces, with numerical accuracy for large numbers of variables and rays. Once a system is optimized, the freeform surfaces can be imported back into Zemax for analysis.

While the nominal optical performance of NURBS systems can be remarkable[5], real-world hardware builds require analysis of sensitivities and tolerances. To that end, we quantify the sensitivities of a NURBS design for a typical wide field imaging flight telescope with an unobscured TMA design by comparing it to equivalent even-asphere and Zernike freeform designs.

Until recently, such TMA telescopes typically used conventional off-axis conic and even-aspheric surfaces to control primary aberrations. Conventional aspheric designs are limited in the field of view they can achieve before developing field-dependent coma and astigmatism. The limits of the conventional aspheric design can be surpassed by making the three TMA mirrors freeform. There are a number of different mathematical formulations for generating and optimizing freeform optical surfaces. One common method, Zernike polynomial freeforms, involves fitting Zernike sag terms to a surface. This method is a built-in Code V or Zemax surface type that can be optimized within the raytracing software package. The Zernike freeform formulation uses polynomial terms that change the sag globally of an entire surface every time a coefficient is perturbed. In contrast, NURBS optimization allows local control of the surface shape using piecewise splines, making them well-suited for optimizing freeform surfaces[6].

2. THREE TMA DESIGNS

We designed three TMAs with equivalent first-order optical properties listed in Table 1. The total ray-defined volume of all three designs is less than 80 liters. The volume is defined by the furthest extents of rays on a given surface. Mirror

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thickness, mounting, structure, etc. are not considered. Off-axis distance of the primary mirror is constrained to be less than 200mm.

Table 1. First order design parameters for all three TMA designs.

Parameter	**Design value**
Entrance Pupil Diameter	200mm
Field of View	4° x 4° square full field
Focal length	600mm
F/#	3
Volume	< 80 liters
Pixel pitch (for analysis purposes)	18µm

2.1 Conventional aspheric design

A conventional TMA design using off-axis even-order aspheric surfaces is shown in Figure 1. The conic constants and even aspheric terms up to 10th order were optimized for all three surfaces. The geometric spot diagrams, RMS WFE field map, and MTF plot are shown in Figure 2 and Figure 3. The telescope is far from diffraction-limited with rms WFE over much of the center of the field of worse than 0.5λ. Even for a large 18µm pixel, the system's nominal design is aberration-limited.

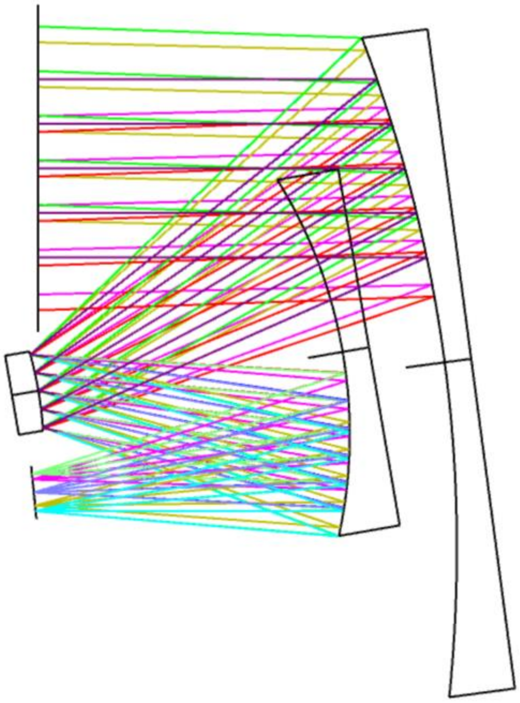

Figure 1. Raytrace of the conventional TMA design with off-axis aspheres. For scale, the entrance pupil diameter is 200mm and the M2 diameter is 90mm.

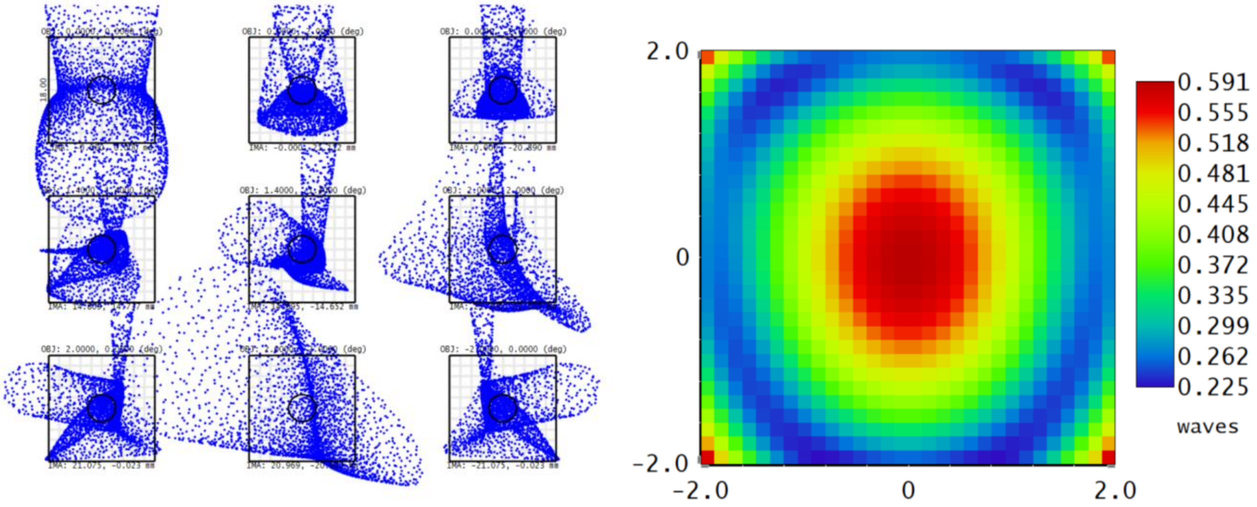

Figure 2. Left: Spot diagrams of the aspheric design. Circles are the diffraction limit and boxes represent an 18μm pixel. The design is neither diffraction limited nor Nyquist sampled. Right: RMS WFE over the 2°x2° FOV in waves, λ=633nm.

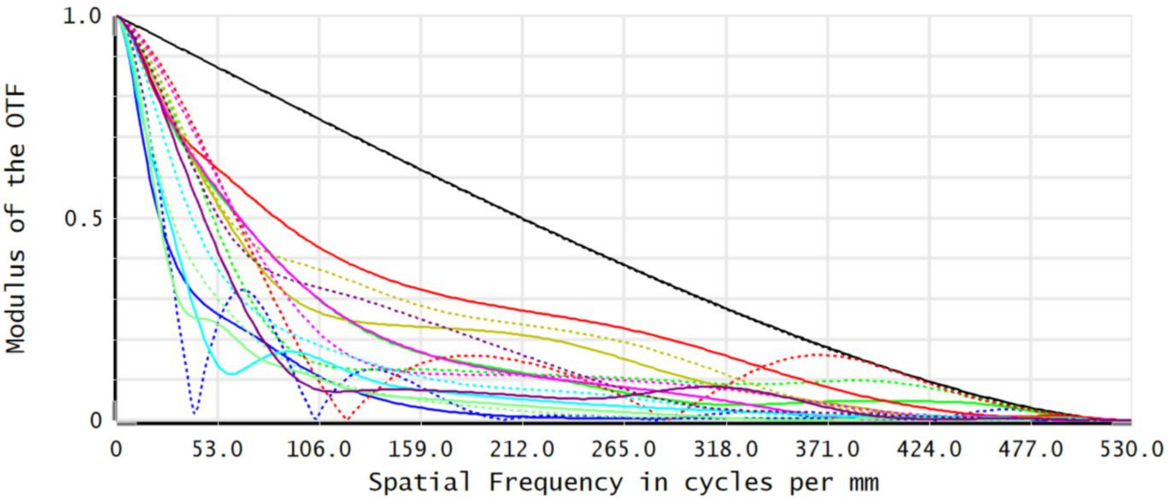

Figure 3. MTF for the aspheric TMA design. Curves are various field points across the 4° field.

2.2 Zernike polynomial freeform design

The raytrace for the Zernike polynomial freeform telescope is shown in Figure 4. This design optimizes up to the first ~30 Zernike coefficients for each surface. Spot diagrams, rms WFE over the field, and MTF are shown in Figure 5 and Figure 6. While the MTF shows that the performance is slightly below the diffraction limit, this system will be detector Nyquist limited for any practical detector.

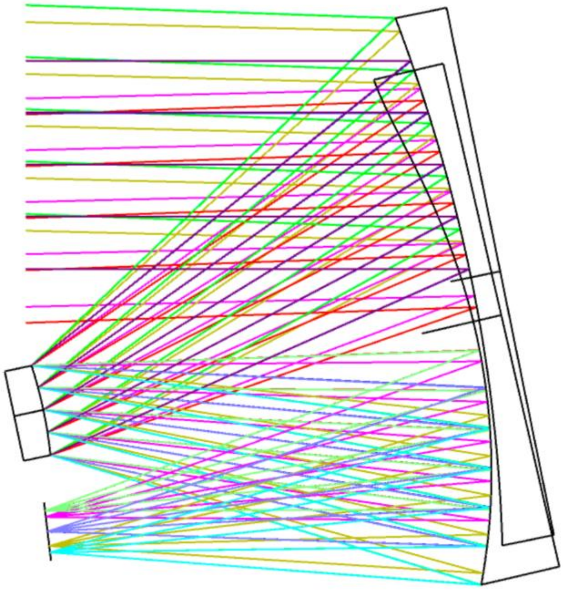

Figure 4. Raytrace of the Zernike polynomial freeform TMA.

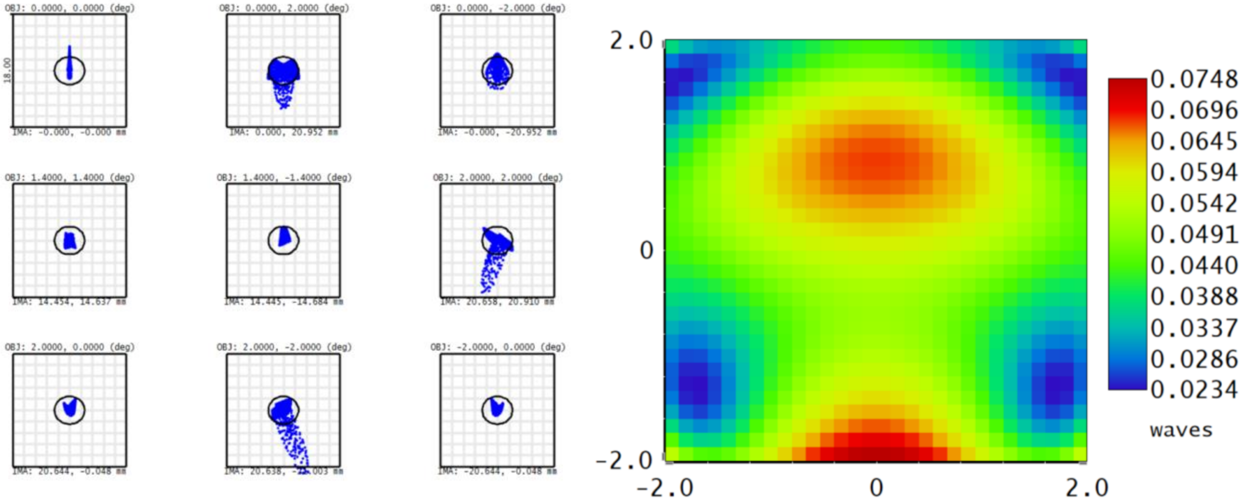

Figure 5. Left: Spot diagrams for Zernike freeform TMA. Circles are diffraction limit, boxes are 18µm pixels. Right: Field map of RMS WFE over the 4°x4° FOV in waves, λ=633nm.

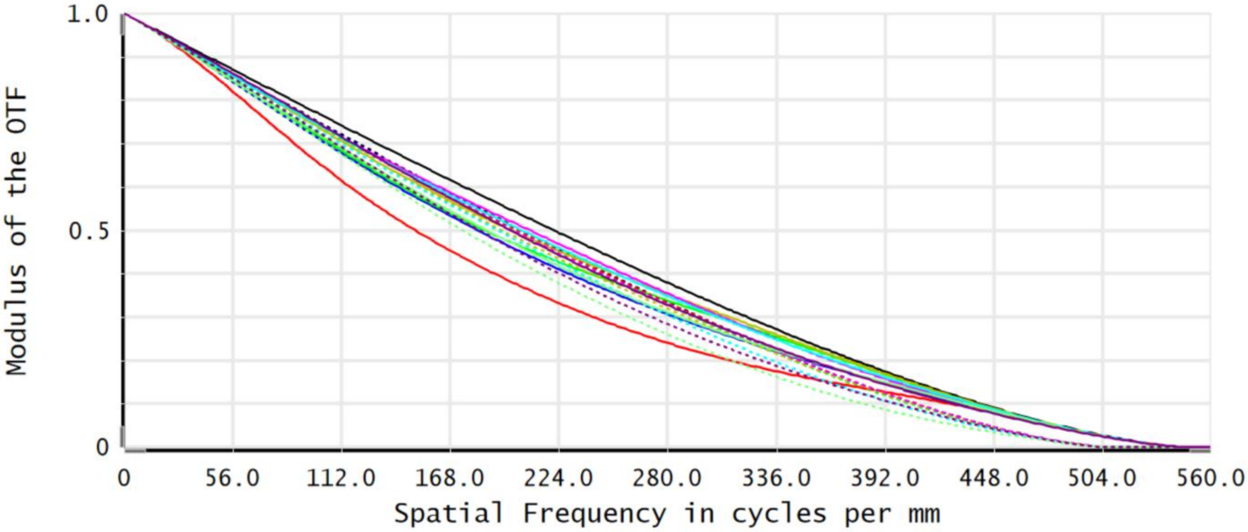

Figure 6. MTF for the Zernike freeform design. Curves are various field points across the 4° field.

2.3 NURBS design

Beginning with the conventional aspheric TMA design as a starting point, a NURBS design was created using FANO. This particular FANO optimization adjusted only the shapes of the three mirror surfaces, not the spacing and position of the mirrors. The optimization was stopped once the average rms spot size over the field surpassed the diffraction limit and performance of the Zernike freeform design. Had it been allowed to continue running, the geometric spot sizes would have approached even-smaller values.

Figure 7 shows the raytrace of the NURBS TMA. Figure 8 and Figure 9 show the NURBS TMA spot diagram, rms WFE over the field, and MTF. With the exception of the very tips of the corners of the field, the MTF curves follow the diffraction limit perfectly.

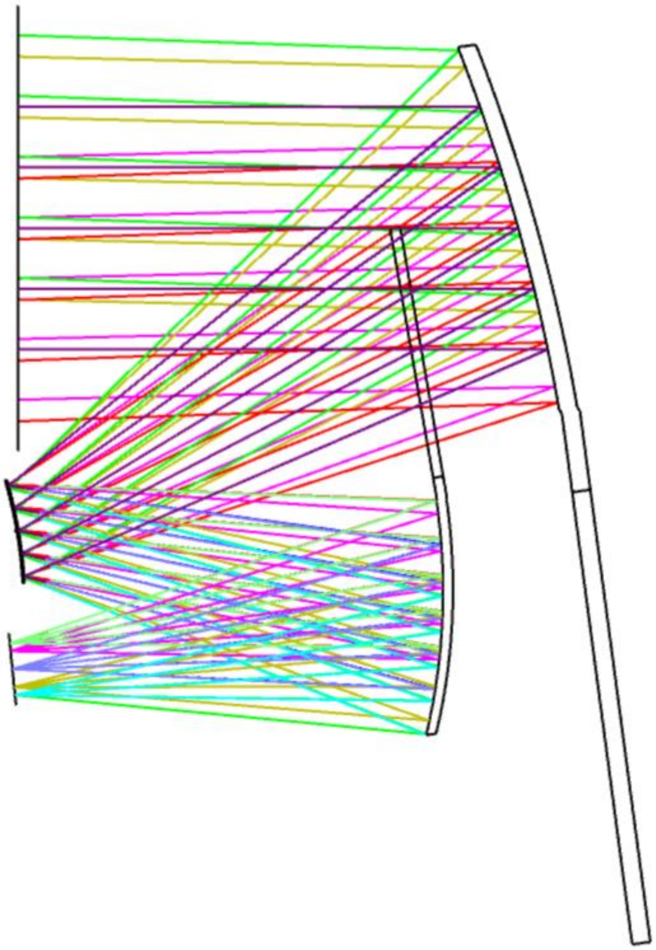

Figure 7. Raytrace of the NURBS TMA design.

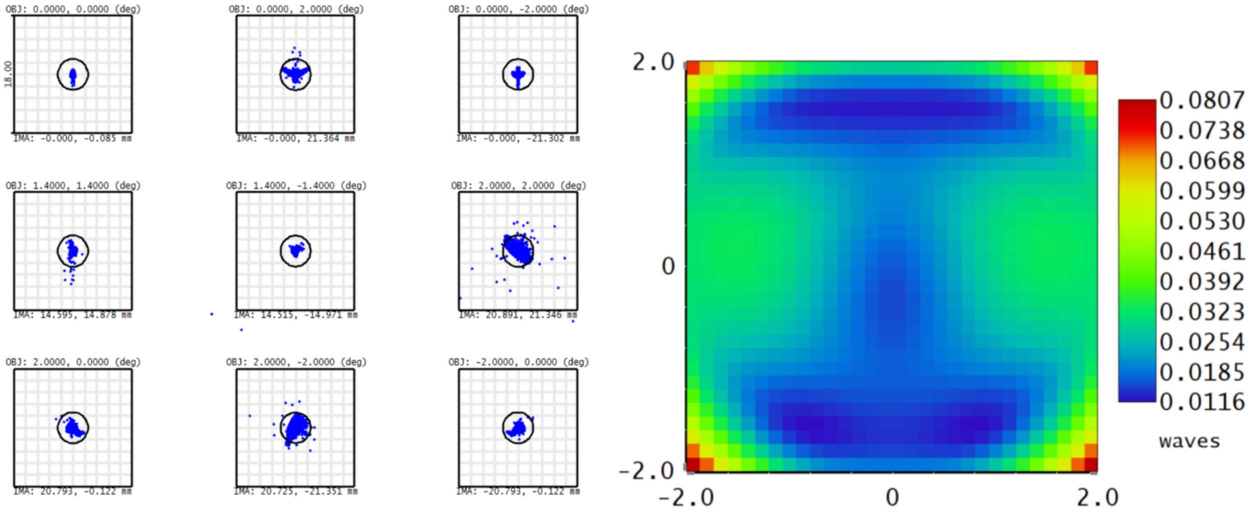

Figure 8. Left: Spot diagrams for the NURBS TMA design. Circles are the diffraction limit, boxes represent an 18µm pixel. Right: RMS WFE field map for the full 4°x4° FOV in waves, λ=633nm.

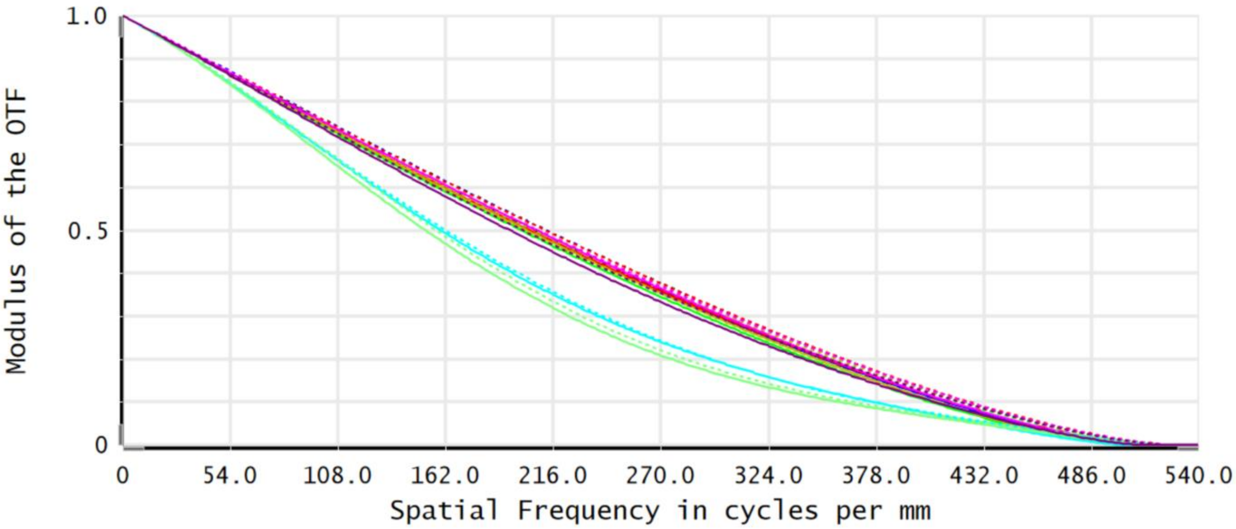

Figure 9. MTF of the NURBS TMA design. Curves are various field points across the 4° field.

3. SENSITIVITY ANALYSIS

We performed a sensitivity analysis on the three designs by perturbing each mirror in 6 DOF. The ϑ_x/ϑ_y/ϑ_z tilts of each element were pivoted about the intersection point of the chief ray with the optical surface (essentially the physical center of the off-axis part). After each perturbation, the tip, tilt, and z-position (focus) of the focal plane were optimized. The figure of merit tracked during the analysis was the mean rms WFE for a 10x10 grid of 100 field points over the full 4°x4° FOV.

The mean rms WFE was chosen as the figure of merit in order to allow as close a comparison as possible between three designs with differing nominal performance. The two freeform designs are at or near the diffraction limit over the field, while the asphere design is close to an order of magnitude worse and aberration-limited. As such, a simple delta-rms spot size comparison would not be valid.

For this analysis, we define the sensitivity of an element DOF to be the mean rms WFE over the field minus the nominal performance of the system subtracted in quadrature. This reverse RSS calculation allows us to compare the small WFE changes from an alignment perturbation to the three systems, despite the large starting aberrations of the aspheric design. These sensitivities are plotted in Figure 10. The mean and RSS of the terms in Figure 10 are listed in Table 2.

Some terms, such as the rotational ϑ_z sensitivities, differ between the three designs, as expected. However, despite the differences in the surface formulation and nominal performance of the three designs, the sensitivities are quite similar, with differences in the mean sensitivity of only a few percent. These forgiving freeform sensitivities are in line with our experience working in the lab with freeform optics and with what others have found in similar analyses[7].

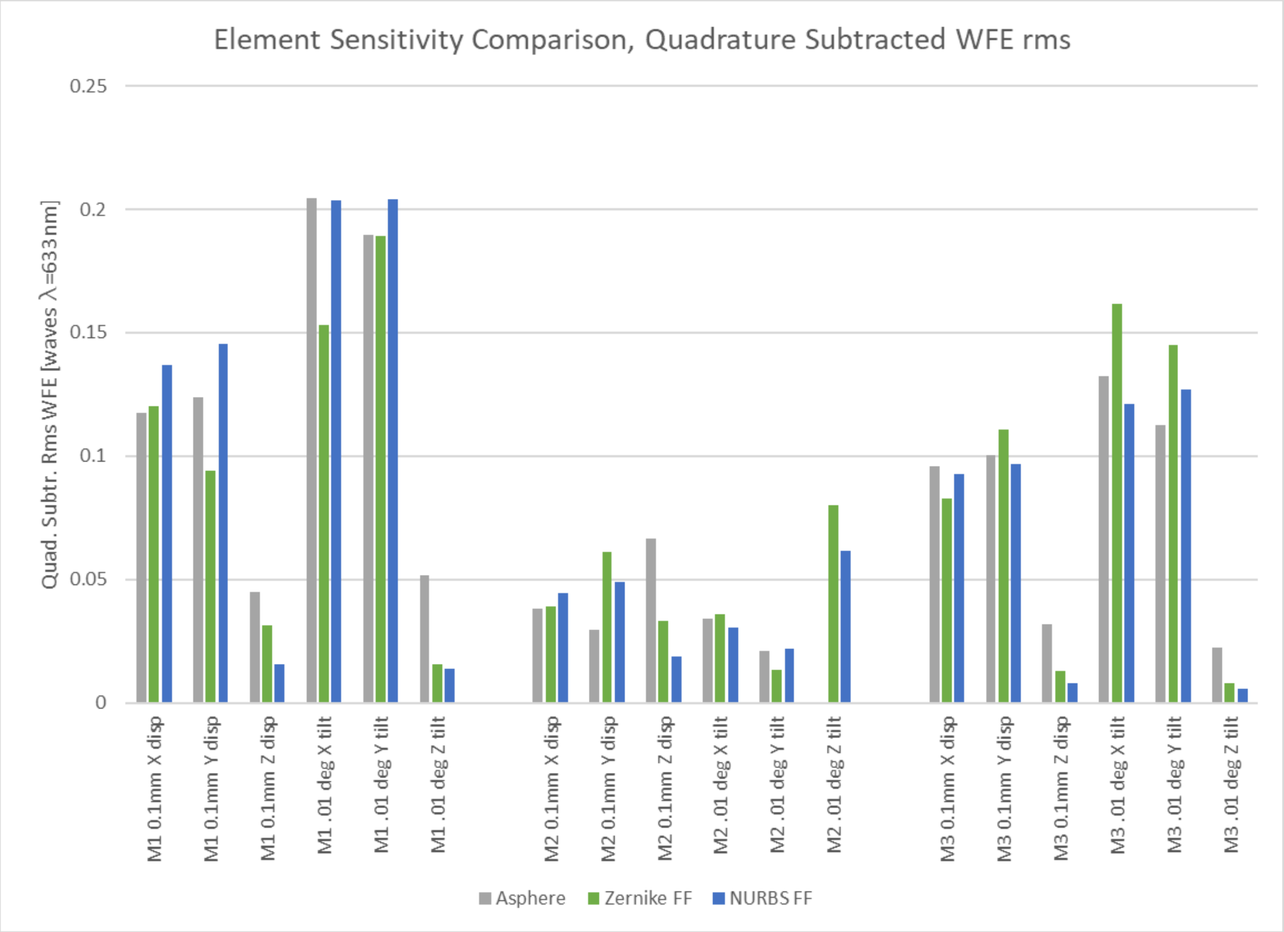

Figure 10. Comparison of the sensitivities for each degree of freedom of each mirror for the three designs. The sensitivities were calculated by subtracting the net mean RMS WFE in quadrature from the nominal performance.

Table 2. Aggregate sensitivity comparison of the three designs. First row is the nominal performance of the unperturbed designs. Second and third rows are the mean and RSS of the terms displayed in Figure 10. Units are in waves [λ=633nm].

	Asphere	Zernike FF	NURBS FF
Nominal mean rms WFE	0.359	0.045	0.029
Mean Sensitivity	0.079	0.077	0.078
RSS Sensitivity	0.414	0.405	0.427

4. THERMAL SOAK ANALYSIS

We performed a thermal soak analysis on the three TMA designs in Ansys Zemax OpticStudio. The image quality of each design was evaluated at three different temperatures: 20°C (the design temperature), 10°C, and 30°C. We used the same figure of merit as for our sensitivity analysis: mean rms WFE averaged over 100 field points over the 4° field of view. However, unlike in the sensitivity analysis, the focal plane position was fixed with no compensation in order to model a system without active focus adjustment. We assumed typical low-expansion materials for the telescope structure, with the coefficients of thermal expansion (CTE) listed in Table 3. The mirrors are modeled as an optical glass with virtually zero CTE, such as Zerodur or ULE.

Table 3. Low expansion structural materials used for thermal soak calculation and their associated coefficients of thermal expansion.

Material	CTE [ppm/K]
Invar 36	1.3
Carbon fiber (typical)	0.5
Graphite epoxy (K13C2U/954-3)[8]	-0.88

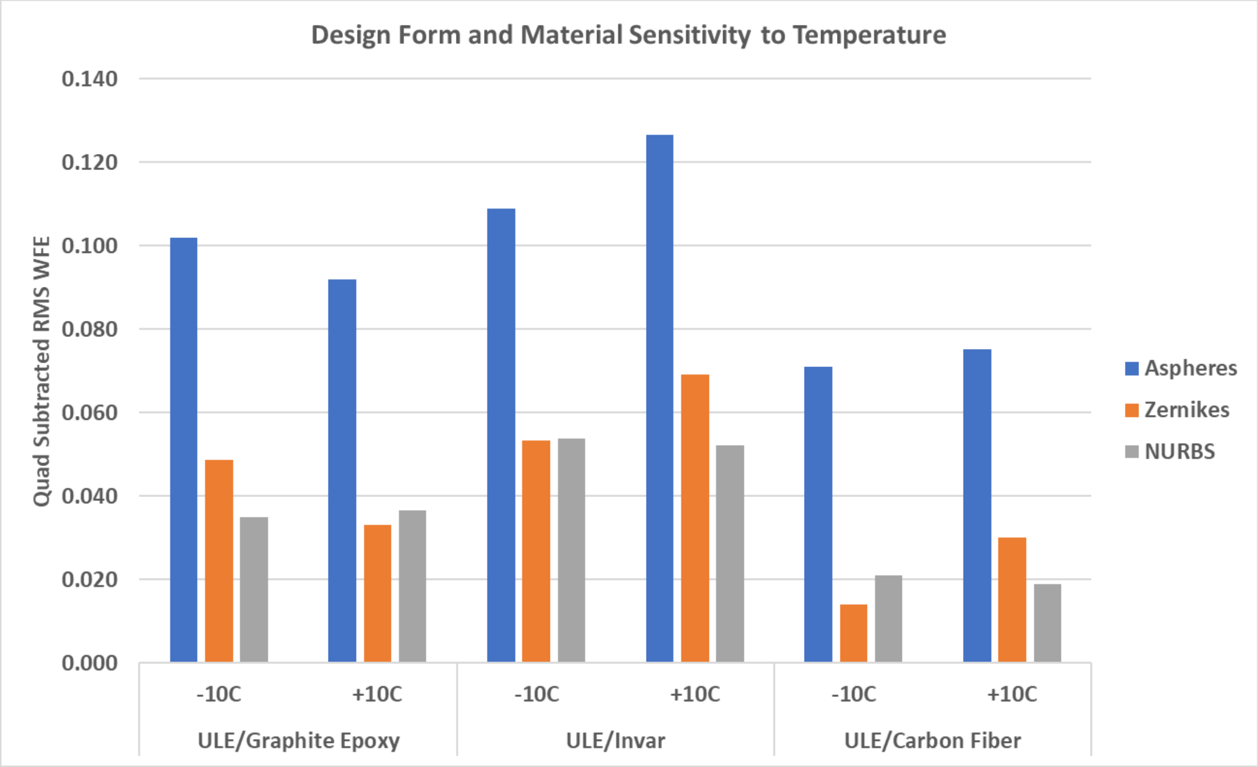

Figure 11. Comparison of thermal sensitivity for the three design forms. Values are the total mean rms WFE minus the design residual subtracted in quadrature.

Figure 11 shows the sensitivity of each design form to a +/- 10°C thermal soak for the three low-CTE structural materials. The sensitivity values are the total resultant mean rms WFE minus the respective design residual, subtracted in quadrature. The NURBS and Zernike freeform designs have similar thermal sensitivity to each other. Both freeform designs are approximately half as sensitive as the conventional asphere design.

5. CONCLUSION

We quantified the alignment sensitivities of a NURBS freeform TMA telescope and compared it to conventional aspheric and Zernike freeform telescopes with similar design form. We found that the sensitivity to misalignment is similar for all three designs, while the NURBS design has superior optical quality overall and a lower rms WFE over the field of view. We performed thermal soak calculations with the three designs using standard low-expansion materials. The two freeform designs were approximately half as sensitive to thermal changes as the conventional asphere design. Our results contribute to a growing body of evidence that freeform designs in general, and NURBS in particular, carry no more alignment and stability risk than telescopes using conventional optical designs.

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