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Optimization for As-Built Performance

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ABSTRACT

Traditionally optical design via computer optimization uses a numerical merit function to represent the optical performance of the simulated system. The conventional design approach is to maximize the nominal performance of the design, and then as a separate step, add fabrication tolerances to the nominal parameters so that upon manufacturing the resulting system still performs to specification. This paper will demonstrate an alternate approach. Because the angle rays make with respect to the normal on each surface are the primary drivers of optical aberrations and tolerance sensitivity, the method uses these ray angle as a fast, numerical approximation for the sensitivity to tolerance defects. This hybrid merit function thus includes the fabrication errors as part of the design process. The resulting design is effectively optimized for as-built, rather than nominal performance. Design examples will be provided which show that optimization using the hybrid merit function yields designs of different forms, which may have inferior nominal performance but superior as-built performance. The resulting alternate designs will be compared to conventional post-design tolerance analysis to demonstrate the reduction in tolerance sensitivity and superior resulting performance.

Keywords: Optimization, design for manufacturing, desensitization, global optimization, optical design, tolerancing

1. INTRODUCTION

Optical design using computer optimization techniques is widely implemented by the construction of a merit function[1], which tabulates all the potential defects, performance goals, specifications, and boundary constraints into a single numerical figure of merit. The goal of the optimization process is to minimize this merit function, which in turn maximizes the desired performance. It is common practice to optimize the optical performance as the first step in the design process, then consider tolerances as a separate step, as suggested in Shannon[2]. When the optical system is built, it is inevitable that some manufacturing defects will be introduced to degrade the performance. These defects may be from incorrect surface shapes, misalignment of the elements, or defects in the materials relative to the idealized model. Traditionally, lens designers seek the best possible nominal design, which allows for the largest performance margin so that once defects are introduced in manufacturing, the resulting as-built system will still meet performance goals.

Optical aberrations generally are introduced from the deviation from linearity in Snell's law. The expansion of the Sine in Snell's Law reveals the nature of these aberrations:

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \cdots$$

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The leading term is the desired linear behavior upon which paraxial optics is based, and the remaining terms are the normally undesirable terms that give rise to third, fifth, and higher order aberrations.

Most performance specifications concentrate on the performance at just the image surface - the sum of all aberrations through the system. Computer optimization thus tends to yield designs which have relatively small sums for the aberrations at the image surface, but larger aberrations at any one intermediate surface. For example (all the examples here were performed with OpticStudio[1)] consider the f/2, 200mm EFL aspheric singlet with zero field of view as shown in Figure 1. The image quality is essentially perfect at the image surface, with nearly zero RMS spot radius. But there is significant spherical aberration introduced at the first surface – roughly 8.5 waves. At the second surface, a compensating amount of spherical aberration is introduced – the same magnitude but opposite sign. The net aberration is zero, but this achieved by a delicate balance of large amounts of aberration. This is how tolerance sensitivity gets introduced – any defect in the surface profile will alter the angles of the rays with respect to the normal, disturbing the aberration balance.

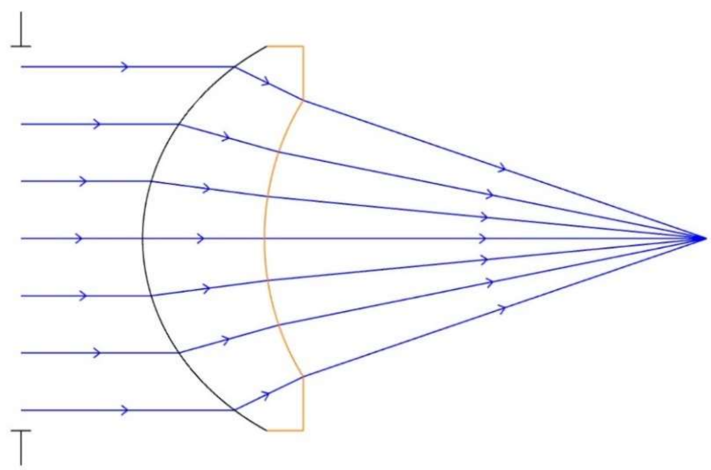

Figure 1 – Singlet with higher ray angles on the first surface

Figure 2 shows a singlet with the same aperture and focal length, also with nearly zero net aberration. This design has much lower ray angles at the first surface.

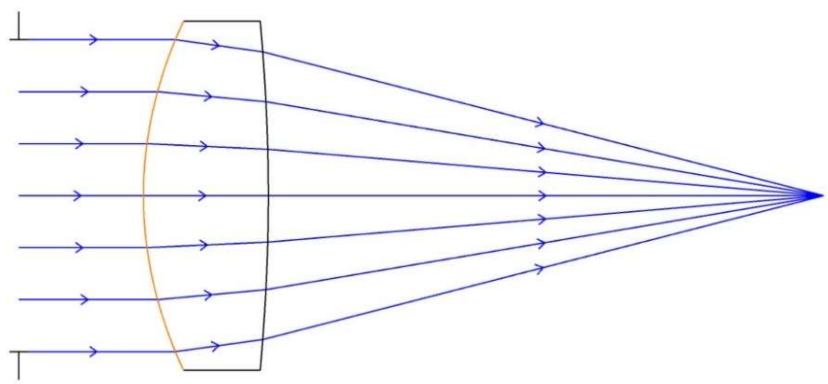

Figure 2 – Singlet with lower ray angles on the first surface

The impact can be seen by a tolerance analysis of these nominal designs. Using identical tolerances (the defaults from OpticStudio) on the two base radii, element decenters, and element tilts, the predicted as-built RMS spot radius is 115 microns for the first design and just 19.3 microns for the second design.

To optimize for best as-built performance, rather than best nominal performance, the tolerance defects must be included in the merit function directly. Including this consideration in the design is potentially very valuable, particularly for global optimization where radically different design forms may be considered that have similar nominal but drastically different as-built performance.

2. PREVIOUS WORK

The idea of optimizing for as-built rather than nominal performance has been well known, but perhaps not widely used for many years. Other authors have suggested methods. Rogers[3,4] describes this phenomenon and introduces the SN2 operand implemented in CODE V[5] to reduce tolerance sensitivity. Rogers described the problem and the SN2 operand, however, the technical details of the method are not revealed. This paper will explicitly state the method proposed.

More recently, Bauman[6] published a method based upon nodal aberration theory and double Zernike polynomials to integrate predicted aberrations into the merit function. The method is numerically highly efficient and returns accurate estimates of increased wavefront aberrations due to defects. These can in turn be used to optimize the design to minimize the contributions of these defects. This approach has many advantages. The method does not however decompose the tolerance sensitivity by surface, and Zernike decompositions may be problematic if the system does not have circular pupils.

The author's own prior work on OpticStudio included the incorporation of the TOLR optimization operand many years ago. That method would compute the entire exact tolerance analysis on the optical system and return the expected as-built performance directly into the merit function. This brute force method works well in theory, but it is slow to optimize using such a lengthy computation that yields just a single number in the merit function.

3. THEORY AND PROPOSED METHOD

This work had several goals. The method must be quickly computed, apply to all types of aberration-inducing surfaces, and be general to all optical systems and not be dependent upon any symmetry or first order properties of the system. Further, it was desired that as many as possible independent components at each surface be retained to be individually optimized, rather than an integrated result over many surfaces or over the pupil or field. The proposed optimization penalty term is

$$\tau = |n - n'|\left(1 - \vec{R} \cdot \vec{N}\right),$$

where n and n' are the indices of refraction before and after the surface, R is the ray direction cosine vector, and N is the surface normal. The dot product of these two vectors yields the cosine of the ray angle to the normal. The cosine expansion is

$$\cos\theta = 1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \cdots,$$

and therefore, the contribution of τ initially goes quadratically with ray angle. The weighting term $|n - n'|$ is added so that surfaces with greater refractive power have increased contribution compared to surfaces with less power, such as cemented glass surfaces. Dummy surfaces where n = n' would not contribute any aberration or tolerance sensitivity and the τ for these surfaces would be zero.

When refracting from a lower index medium to a higher index medium, such as from air to glass, the incident ray cosines should be used. When refracting from a higher index medium to a lower index medium, such as from glass to air, the exit ray cosines should be used instead. This selection will yield the larger angle and the greater value for τ at all surfaces.

When tracing rays in a merit function to compute RMS spot radius or wavefront, the values R and N at every surface are already known, and so very little additional computation is required to compute τ. The merit function is not significantly slower to compute than when evaluating the traditional image surface only criteria. Furthermore, the same techniques used to integrate aberrations over the entrance pupil may be used. The identical ray grid may be used to integrate the RMS τ over all surfaces as well as the net image aberration. The excellent Gaussian Quadrature method by Forbes[7] may be used here for this purpose. The factor τ defined above has been implemented into OpticStudio as the "HYLD" (for High Yield) operand and the results this technique produces will be described.

4. DESIGN EXAMPLE #1

The first example will be the design of a lens with the following specifications: 9 all spherical air spaced elements, stop after the 5th element, f/3.0, EFL 100.0 mm, full field of view 28.0 degrees, visible wavelengths (F, d, and C). Boundary conditions are 2.0 mm minimum air and edge thickness and 100.0 mm maximum center thickness for both glass and air, no more than 1.0% distortion, and no vignetting. A random subset of 60 Schott Preferred glasses was used as a custom glass catalog. This reduction was done to increase the probability that a design close to the global optimum would be found in a reasonable amount of time. The optical performance goal was minimum RMS spot radius, averaged across all fields and wavelengths. Gaussian Quadrature was used to calculate the RMS values.

Starting with parallel plates, the design was optimized using the OpticStudio Global Search algorithm for about 4 hours on a modest 4 core computer. All radii and spacings were made variable, and all glasses were automatically selected from the subset catalog. There is no way to know if the design that was found is the global optimum (for these specific restrictive specifications), however after about 30 minutes of run time no significant decreases in the RMS were observed. The resulting design is shown in Figure 3.

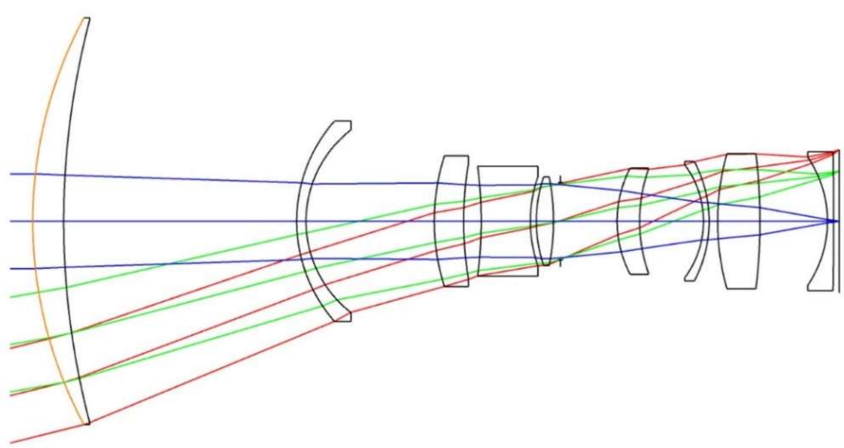

Figure 3 – Best design found for Example 1

A tolerance analysis was then performed on this candidate design, using the loose default tolerances in OpticStudio. All default tolerances and settings were used. The default tolerance analysis considered 181 possible defects, including potential specification, irregularity, and alignment errors. To simplify this discussion, only two computed values will be considered – the nominal RMS spot radius for the perfect design, and the as-built RMS spot radius estimated from the Root-Sum-Squared analysis of all 181 of the individual sensitivities. For the above example, the nominal RMS is 1.89 microns, and the as-built RMS is 106.3 microns. The substantial loss of performance is a combination of the loose tolerances as well as the unconstrained high ray angles at some surfaces.

Starting from the same design and specifications as the previous example, the new HYLD operands to optimize for as-built performance were added to the merit function, and the identical design procedure repeated. The new design is shown in Figure 4.

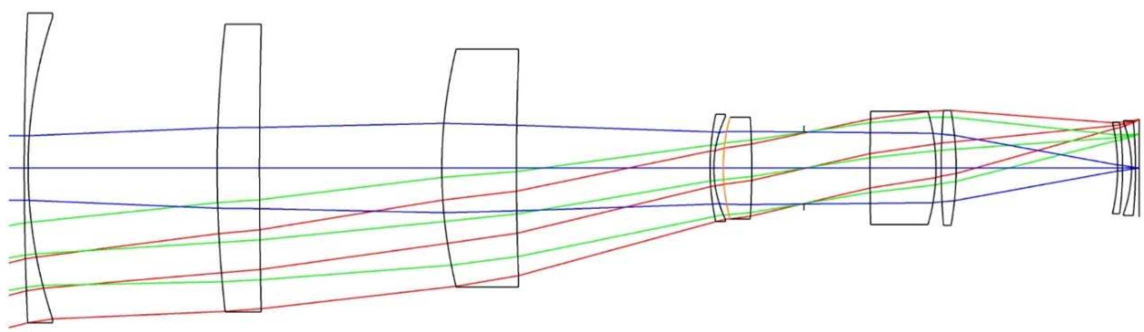

Figure 4 – Best design found for Example 1 with HYLD

The same tolerance procedure as the previous design was repeated. The new design has a nominal RMS of 5.34 microns, and an as-built RMS of 29.7 microns. The nominal performance is significantly worse for the HYLD design, but the as-built performance with these default tolerance defects is a substantial improvement. This is the key message of the HYLD method – the optimization sacrifices idealized performance in exchange for improved as-built performance. Further, the resulting design forms with and without HYLD may be radically distinct.

5. DESIGN EXAMPLE #2

For Example 2, the same specifications and catalogs as in Example 1 were used, with the following exceptions: 10 elements were used, stop after the 4^{th} element, f/2.0, total lens length must be 180 mm. The design was again optimized for 4 hours for minimum RMS spot Radius (no HYLD) and the best design found is shown in Figure 5. The nominal RMS is 3.26 microns, and the as-built RMS is 111.5 microns.

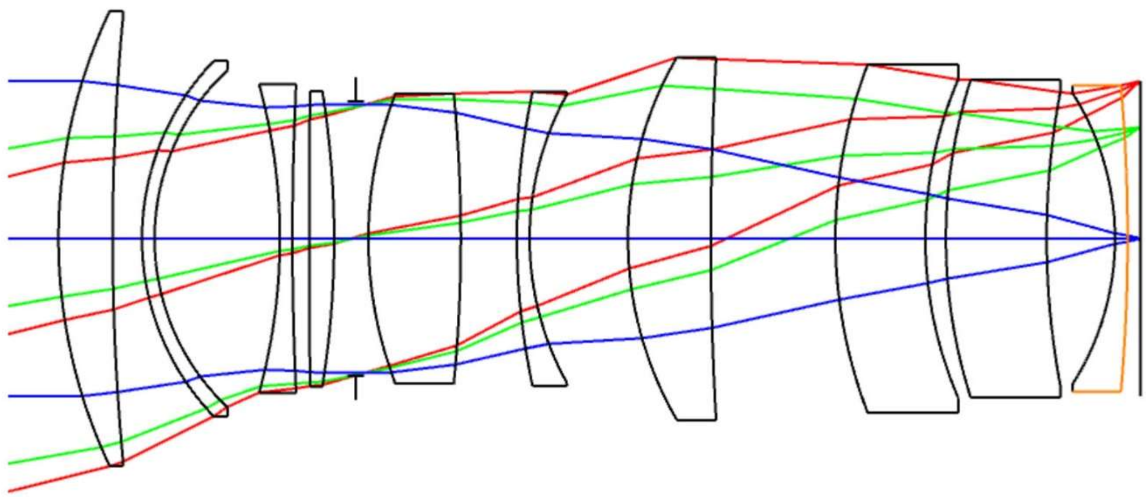

Figure 5 – Best design found for Example 2

The optimization was repeated using the HYLD merit function. The resulting design is shown in Figure 6.

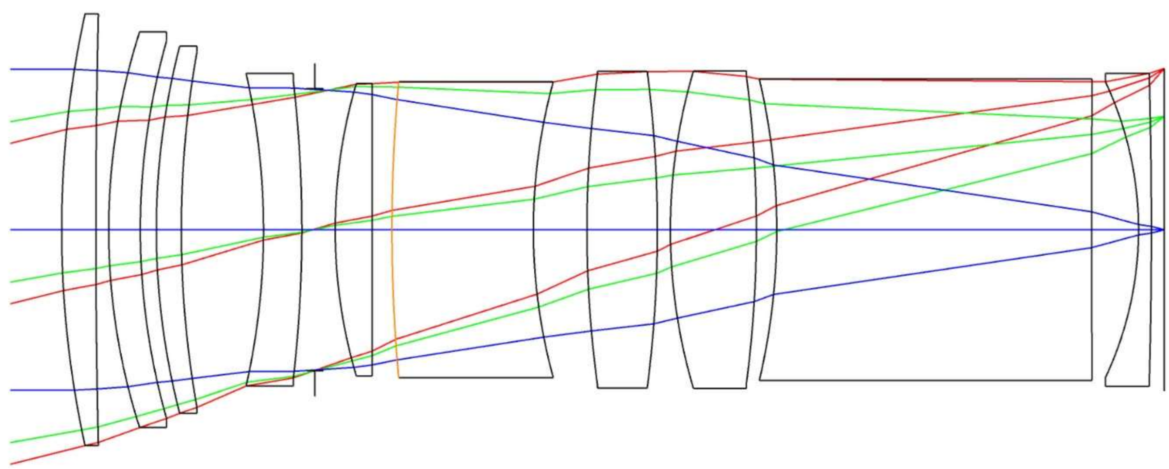

Figure 6 – Best design found for Example 2 with HYLD

For this hybrid merit function design, the nominal RMS is 11.1 microns, and the as-built RMS is 36.9 microns. Again, nominal performance is sacrificed for much better as-built performance.

6. DESIGN EXAMPLE #3

For Example 3, the field of view was increased to 36 degrees, only 7 elements were used, stop after third element, the restriction on overall length was eliminated, distortion of up to 2% was allowed, and the merit function was set to optimize RMS wavefront error instead of RMS spot radius. The optimization and tolerancing procedures were the same as used in the prior examples. The best design found is shown in Figure 7. The nominal RMS is 1.72 waves, and the estimated as-built RMS is 9.96 waves.

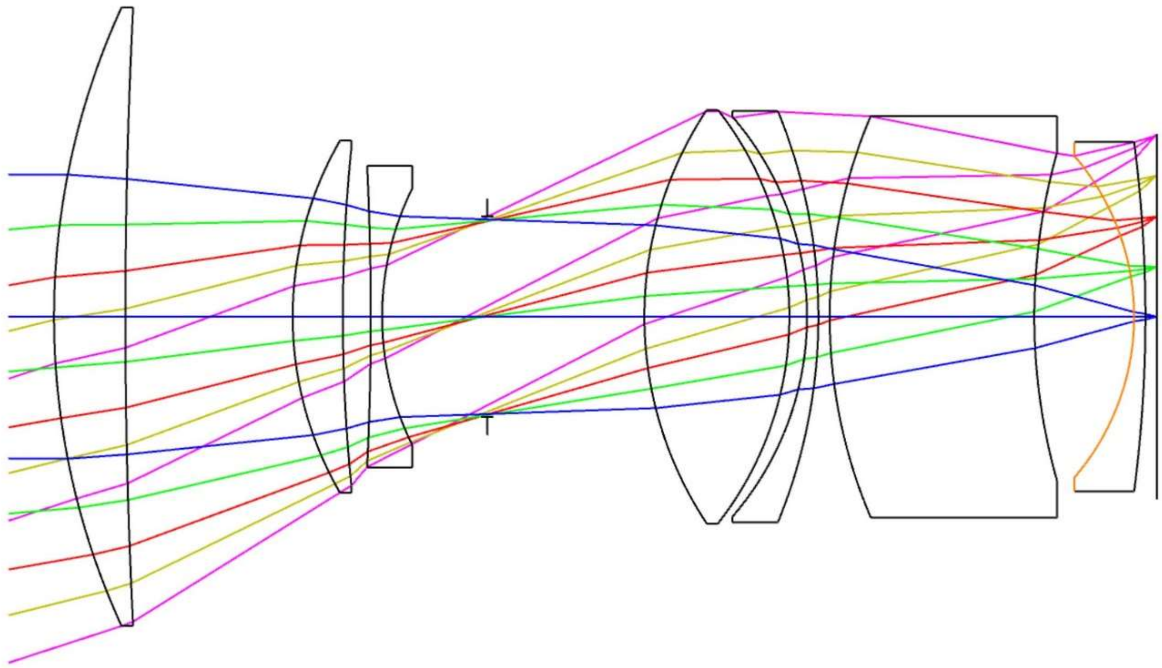

Figure 7 – Best design found for Example 3

The corresponding best design using HYLD is shown in Figure 8.

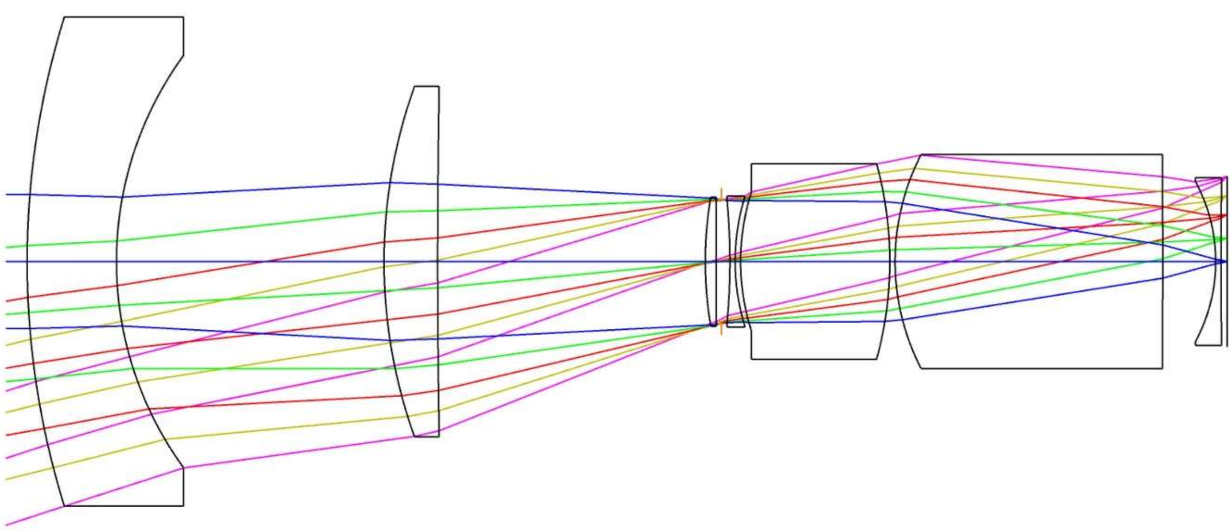

Figure 8 – Best design found for Example 3 with HYLD

For this modified Example 3, the nominal RMS is 2.24 waves and the as-built RMS is 5.48 waves. The HYLD method again produces a worse nominal performance design but a better as-built result.

7. TOLERANCE CONSIDERATIONS

The dramatic results presented here are partially due to the loose tolerances used in the tolerance portion of the analysis. In practice, as the tolerances become tighter, the benefits to using the HYLD method will decrease. In the limit of extremely tight tolerances, the HYLD method produces worse as-built performance because there is no benefit in constraining ray angles if no manufacturing defects will subsequently disturb the aberrations induced by refraction through these surfaces.

8. OPTIMIZATION AND WEIGHTING

The HYLD operand, like all operands in the OpticStudio merit function, may be user-weighted. Setting the HYLD weight very low yields the best nominal performance. If the HYLD operands are weighted very heavily, then the optimization process tends to produce designs that do not focus light at all – the rays will tend to be normal at every surface. The optimal weighting is an open area of research. The best weight will be a function of how tight the tolerances will be, what the desired yield is, what type of nominal merit function is used, and the unique properties of the system. Different common image quality merit functions include RMS wavefront, spot radius, or MTF – and these all have different units of measure. In practice, the weight is insensitive over reasonable ranges, and the default weight of 1.0 works fine and was used for all these examples.

9. SUMMARY AND CONCLUSION

The proposed method adds consideration of ray incident or exit angles to the design process. This method was implemented into the HYLD operand in OpticStudio, however the method applies to any ray-based optimization algorithm. The HYLD optimization method is a fast, efficient way to design lenses with lower tolerance sensitivities than conventional nominal performance optimization. Although the resulting designs have worse nominal performance, the reduced angular sensitivity leads to improved performance in the as-built system.

10. ACKNOWLEDGEMENTS

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