ACTIVE OPTICAL SYSTEMS

AN038

Imaging Lens Array Focal Plane for SHWFS

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Revision: 9/19/21

1 Introduction

Adaptive optics systems can only run as fast as the camera acquisition rate. High speed AO systems often require that the Shack-Hartmann wavefront sensor camera read out a reduced number of pixels to achieve a high frame rate. Unfortunately, COTS lens arrays do not have a pitch that will always match the desired number of pixels per sub-aperture. This can be overcome by reimaging the lens array focal plane onto the camera with a desired magnification. This application note describes some of the key optical concerns with designing such an imaging system and proposes solutions.

2 General Optical Configuration

Figure 1 shows the general optical configuration for imaging a lens array focal plane to a camera for controlling the pitch on a Shack Hartmann Wavefront Sensor (SHWFS). Light from the lens array comes to a focus. This focal plane is then imaged onto the camera using an optical system that imbues the desired magnification to the image of the lens array focal plane.

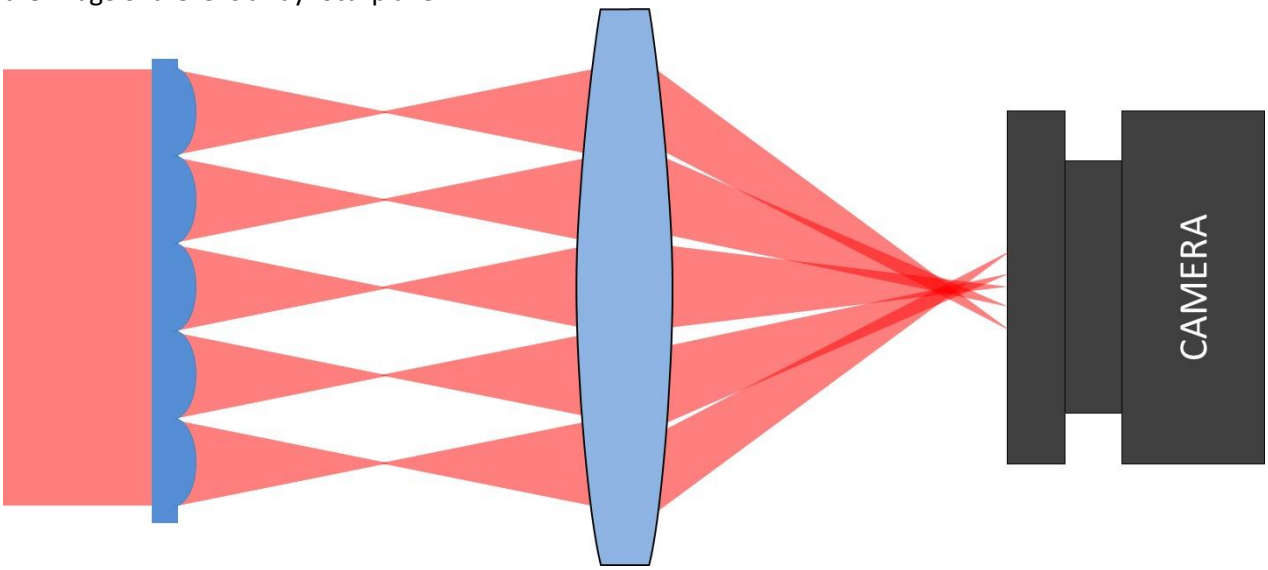

Figure 1: General Lens Array Reimaging Configuration for SHWFS

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3 Single Lens Imaging

In simple situations, this kind of imaging can be accomplished with a single lens. The lens choice is critical for achieving good results. Figure 2 shows a table summarizing how different lens shapes perform with different magnifications (conjugate ratios).[1] For many designs, the bi-convex shape is effective. Plano-convex and best form can also be effective depending on the design. All of these should be modeled in a ray-optics tool like Zemax OpticStudio to gauge efficacy.

Lens	Focal Length	Conjugate Ratio	Chromatic Aberration Correction	Applications
Spherical Singlet Lenses				
Plano-Convex	Positive	5X - Infinite	-	Focusing a Collimated Beam; Collimating a Point Source
Bi-Convex	Positive	0.2X - 5X	-	Relay Imaging (Real Object and Image); Focusing a Divergent Beam
Plano-Concave	Negative	5X - Infinite	-	Diverging a Collimated Beam; Collimating a Convergent Beam
Bi-Concave	Negative	0.2X - 5X	-	Relay Imaging (Virtual Object and Image); Diverging a Convergent Beam
Best Form	Positive	Infinite	-	Focusing a Collimated Beam; Collimating a Point Source
Achromatic Lenses				
Cemented Achromatic Doublet	Positive	Infinite	Good	Broadband Focusing and Collimation; Improved Monochromatic Performance
Air-Spaced Doublet	Positive	Infinite	Better	Broadband Focusing and Collimation; Optimized On-Axis Performance; High-Power Applications
Cemented Doublet Pair	Positive	1X - 3.33X	Good	Broadband Relay Imaging (Real Object and Image); Improved Monochromatic Performance
Cemented Achromatic Triplet	Positive	1X - Infinite	Best	Broadband Focusing, Collimation, and Relay Imaging; Correction of All Primary Chromatic Aberrations
Aspheric Lenses				
Aspheric Lenses	Positive	Infinite	-	Optimized On-Axis Performance; Laser Diode Collimation; Fiber Coupling
Aspheric Lens Pairs	Positive	1X - 3.66X	-	Optimized On-Axis Performance; Relay Imaging (Real Object and Image)
Aspheric Condensers	Positive	Infinite	-	Light Collection; Collimation of Incoherent Light

Figure 2: Table of Common Lens Shapes and their Most Effective Conjugate Ratio (Magnification) Ranges

As an example, we will consider a lens array with a NA of 0.01 (f/50) and a wavelength of 550nm being reduced by 4x to the image plane. Application Notes 5 (AN005) gives us simple ray matrix design approaches for designing this system. For this single-lens design, the lens law (1/f=1/d1+1/d2) coupled with the magnification definition (M=d1/d2) is sufficient. There is a calculator that will make this easier on the Google Play store.[2] Using the calculator, we find that the two distances for a 4x magnification are 125mm and 500mm.

The first lens we will consider is a bi-convex 100mm focal length lens from ThorLabs (LB1676). For simplicity of this example, we set the initial distance to a total of 500mm, set the paraxial image height of the secondary field to 1.0mm (corresponds to about 3.92mm Object Height), set the system to telecentric object space, and optimized the focal spot by adjusting the image distance. Figure 3 shows the results obtained in Zemax. The on-axis field produced a cluster of rays that were all inside the black Airy ring (diffraction limit). The off-axis field shows the spot flaring away from the center as is often the case in this kind of imaging.

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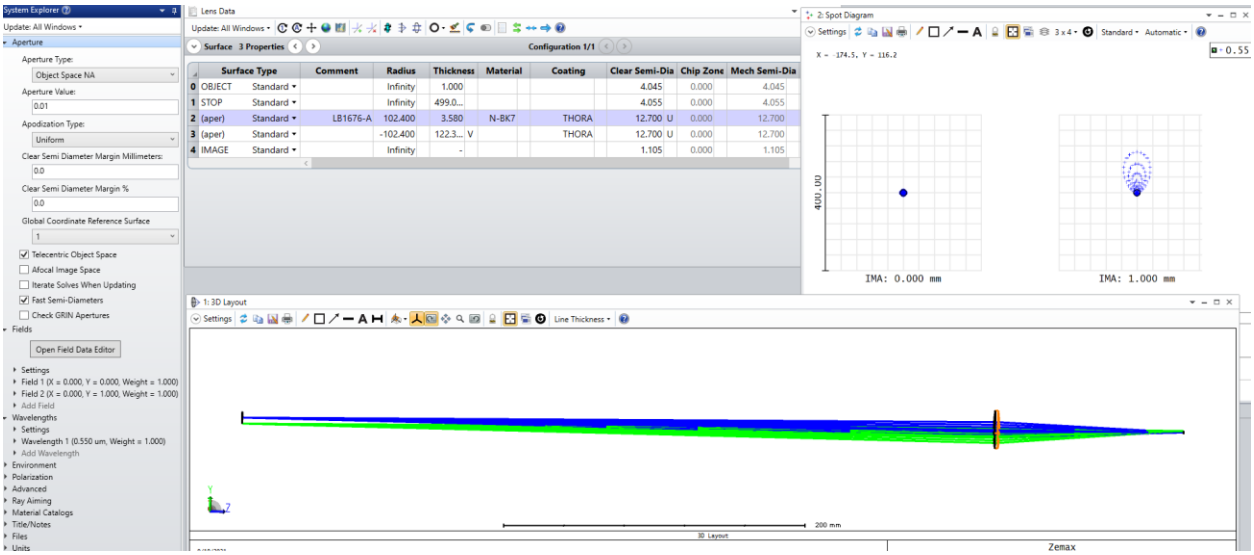

Figure 3: Zemax Results for Imaging with a ~4x Magnification using a Bi-Convex Lens System

Repeating the test with a 200mm focal length bi-convex 2" diameter lens (LB1199 from ThorLabs), we get slightly better results. The initial distance was set to 1000mm. The solved final distance for best spot was now 244.8mm. The magnification was about 3.97. Figure 4 shows the results using this optical configuration from OpticStudio. The spot flare off-axis is less relative to the Airy circle, but not entirely gone.

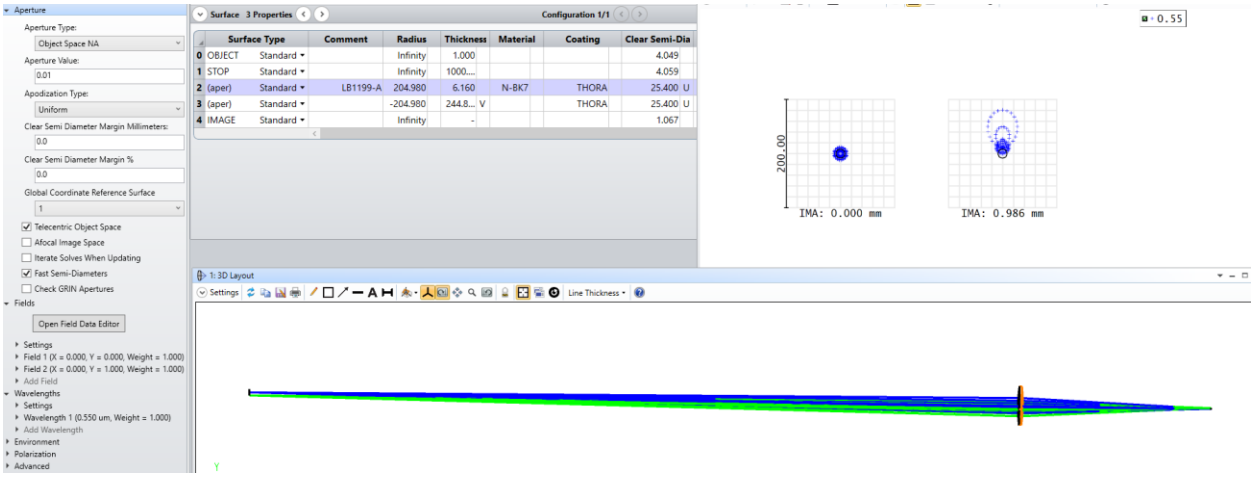

Figure 4: 4x Imaging Results with a 200mm Focal Length Bi-Convex Lens

Repeating the analysis with a 200mm focal length plano-convex lens (LA1979) produces similar results. Figure 5 shows the results of the OpticStudio modeling. We again see the flaring away from the center with a similar magnitude to the bi-convex lens case.

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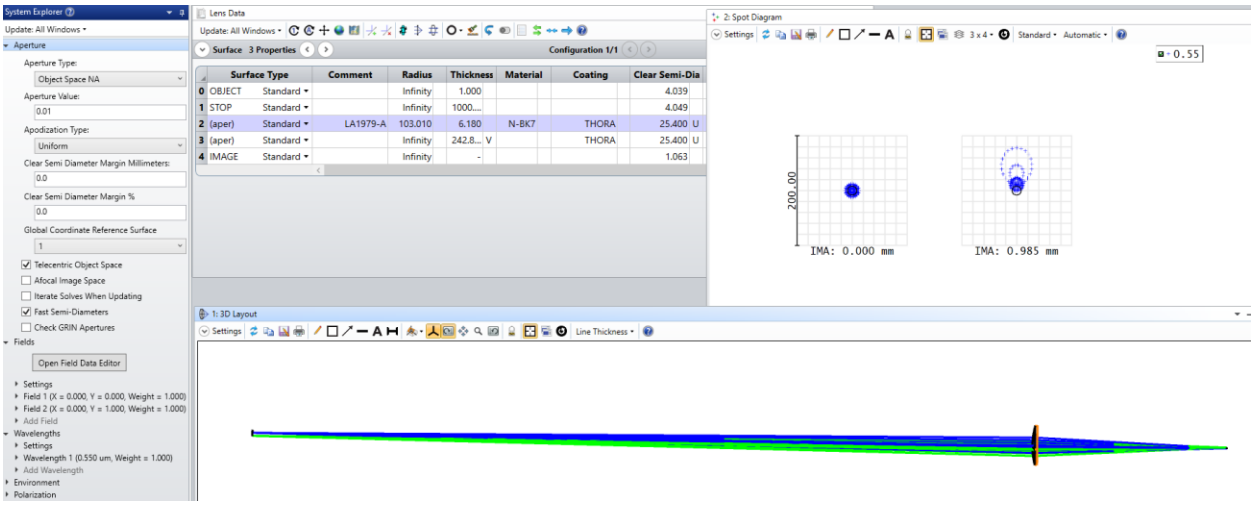

Figure 5: Plano-Convex 4x Imaging with a 200mm Focal Length Lens

The longer focal length designs were effective at achieving somewhat acceptable results, but were extremely long optical systems. We will now consider an achromatic lens instead of the single-element lenses. We will go back to a 1" diameter 100mm focal length (AC254-100-A) architecture. Again, we set the initial distance to 500mm and sovled for the best spot by varying the image distance. We achieved a magnification of 3.92 at 121.9 mm image distance. Figure 6 shows the OpticStudio results. This imaging system still had the flare away from the center in the rays at the edge of the image plane, but both the on and off axis spots were significantly better than the single element lenses. This is likely attributable to the multi-element nature of the achromatic lens. The overall length of this system is around 630mm (25"), which may be too large for some use cases. In the following section, we will try to make it shorter.

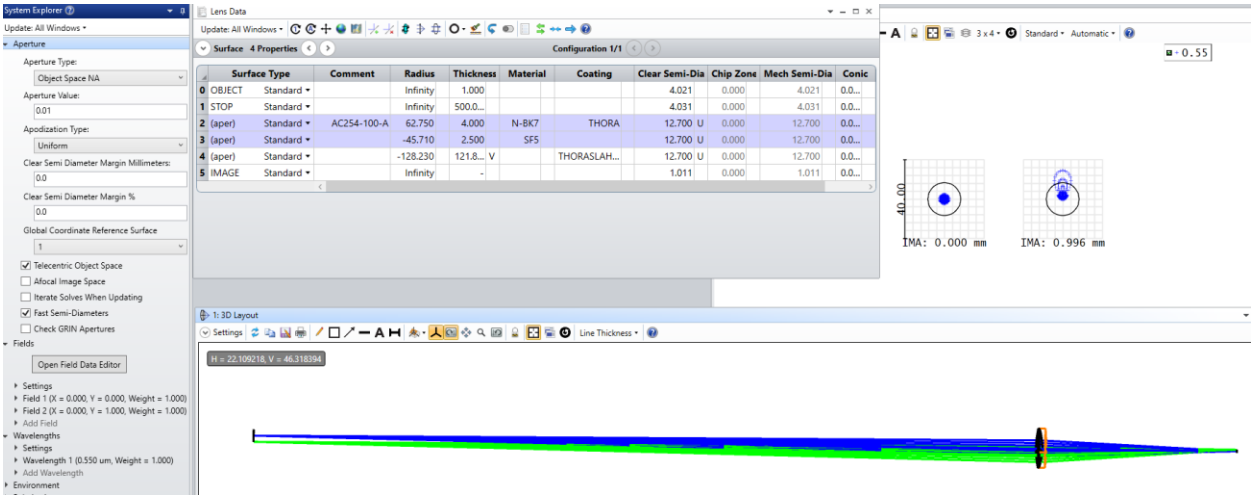

Figure 6: Achromatic Single Lens Imaging for 4x Magnification

4 Matched Achromatic Pair Imaging

The single lens imaging systems were effective at producing good results, but in a fairly long optical system. To reduce the optical system length, we will explore using multiple lenses to reduce the system. The configuration we will use is referred to as a matched achromatic pair (MAP). The MAP system simply places two achromatic lenses back to back with a nearly collimated beam between them. The focal lengths of the

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lenses are chosen like that of a telescope system where the ratio is equal to the desired magnification. This approach uses the achromatic lenses in the infinite conjugate configuration in which they are design to perform well. The object plane is placed at the focus of the first lens and the image plane is at the focus of the second lens.

We will again try to create a 4x imaging system. We will initially be aggressive in the focal length ratio choice to see if we can achieve good results with a much shorter system. We will choose a 25mm and 100mm focal length. The total length of this system can now be about 6" instead of the 25" single lens design presented above.

Figure 7 shows the results of achieving collimation after inserting the first lens. The initial distance was set to be variable and the wavefront was optimized. The Afocal Image Space option was selected. The Telecentric Object Space option was deselected. The PV WFE is only 0.0054 waves. After optimization, the initial distance was fixed to 97.067mm. It was important to orient the lens with the flatter surface closer to the object (focal plane of the lens array).

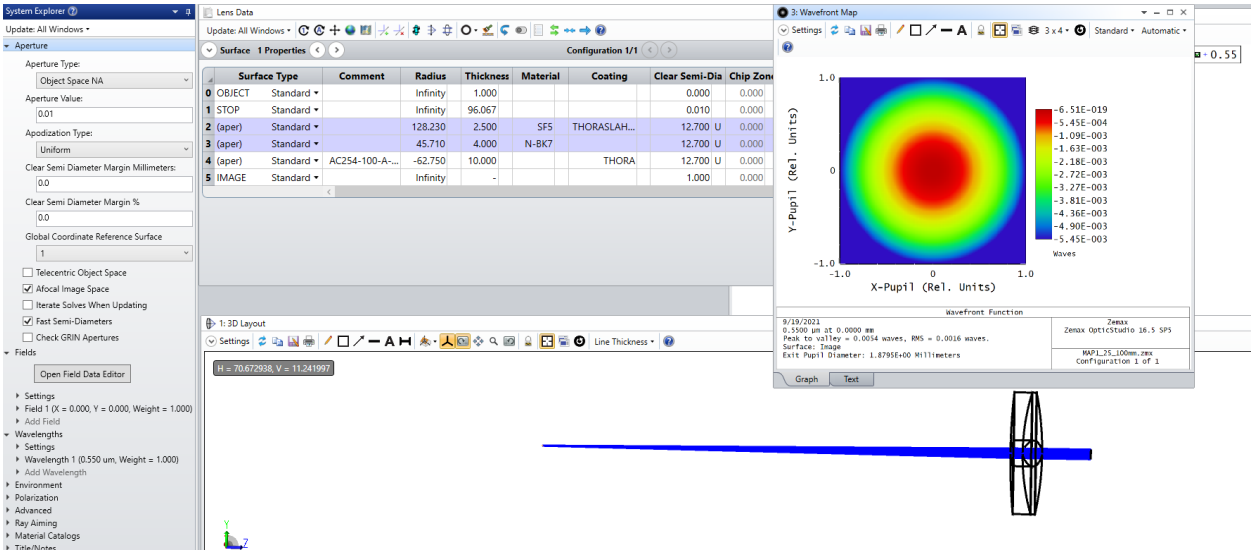

Figure 7: Achieving Field Collimation on the 100mm Focal Length Achromatic Lens

Next the 25mm focal length achromatic lens (AC127-025-A) was inserted with the more curved surface toward the first lens. The final distance was set to variable. The Afocal Image Space was deselected. The Telecentric Object Space was selected. The optimization was set to achieve best focal spot. The magnification achieved for this configuration was 3.91x when the final distance was 21.461mm. The off-axis field was added to show the performance at the edge of the imaging system. Figure 8 shows the results achieved with OpticStudio. The central ray bundle collapsed into a sub-diffraction-limited cluster. The ray bundle that was 1mm off-axis in the image plane is larger than diffraction limited, but only slightly. Again we see the flaring away from the center likely associated with spherical aberration.

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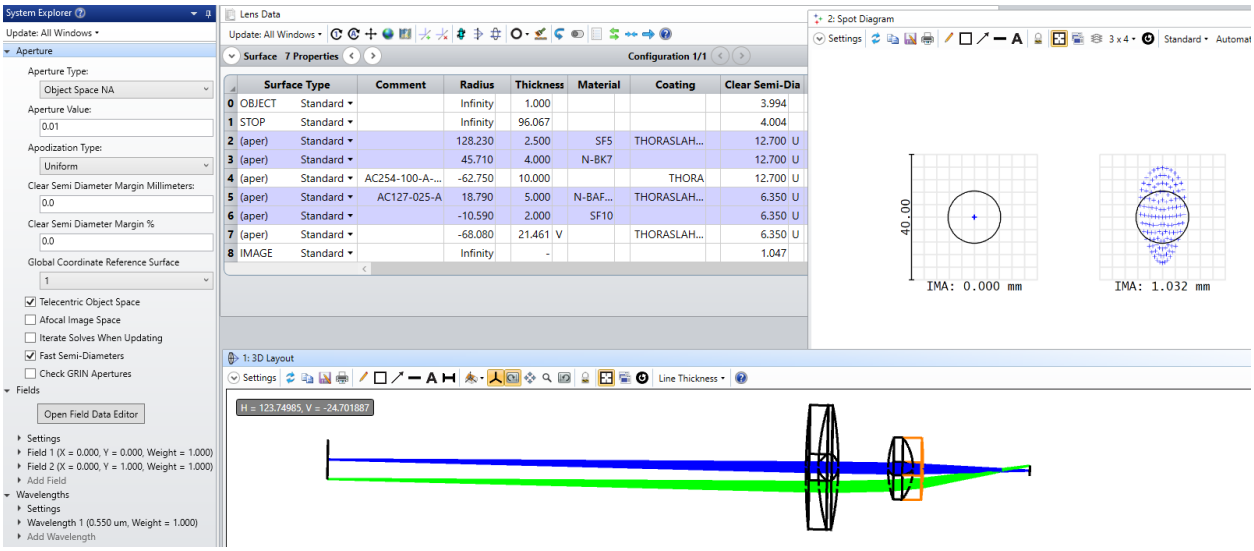

Figure 8: MAP System Image Performance with 25mm and 100mm Focal Lengths

To see if a longer focal length pair would be effective, we tried analyzing a 50mm and 200mm MAP system. We first placed the 200mm lens and optimized the wavefront is afocal image space. The result was a PV WFE of 0.0161 waves. Then we placed the 50mm lens and optimized the spot. We again achieved a 3.9x magnification. Figure 9 shows the OpticStudio results of the longer design. The on-axis bundle was again well inside the Airy disk. The edge ray bundle achieved the majority of the rays in the Airy disk, but did have some leaking out the edge. These results are significantly better than the 25mm-100mm MAP results, but the resulting system is close to 11" long.

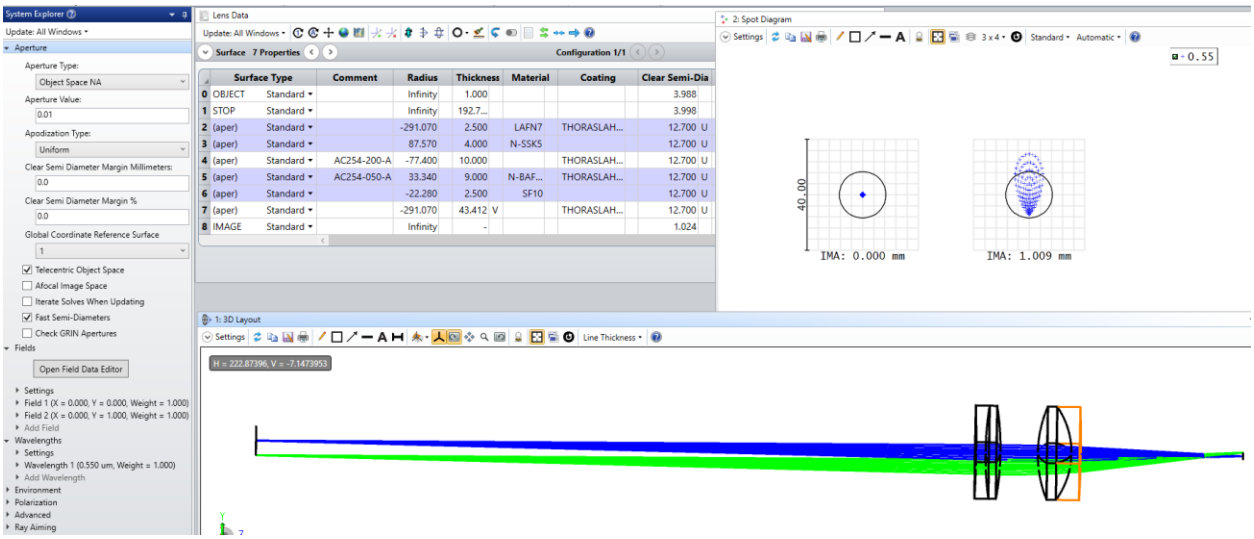

Figure 9: MAP Imaging Results with a 50mm and 200mm Focal Length Pair

5 Telecentric Imaging System

On several occasions we have explored the potential for using a telecentric imaging system for imaging the focal plane of the lens array to the camera. This would provide the benefit of the rays entering the camera being parallel instead of spreading as they approach the camera. The cost and complexity of these imaging systems has always pushed us away from this approach, but we believe that it has merit.

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6 Conclusions

In this application note, we have explored several different ways of imaging a lens array focal plane onto a Shack-Hartmann wavefront sensor. Although the single lens systems were simpler and more cost effective, the matched-achromatic-pair (MAP) results were significantly better and required much less propagation distance. We would recommend the MAP approach for most systems because it gives superior results with minimal distance.

7 References

[1] https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=8790
[2] https://play.google.com/store/apps/details?id=aos_llc.imagingdesign

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