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Depth of Focus Extension Wavefront Coding Methods for Fast Imaging Systems

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ABSTRACT

We compare different methods to extend the depth of focus of a fast infrared imaging system. Instead of using a phase mask for wavefront coding, we place this element directly on an optical surface.

Keywords: Wavefront coding, depth-of-focus extension, end-to-end design

1. INTRODUCTION

In 1995, Dowky and Cathey proposed the use of a phase mask to increase the depth of field of an optical system.¹ This method generates a depth invariant Point Spread Function (PSF), but also degrades the image quality. A digital processing that restores the image is therefore necessary, and when this processing is optimized together with the optical system, it is referred as “end-to-end design”.² Today, deep-learning and neural network approaches are particularly used, and they are improving by allowing the study of optical systems with more aberrations.³

In this paper, we propose to extend the depth of focus (DoF) of a complex imaging system, with a large aperture, without using additional optical surface. This excludes “phase mask” approaches,^{2,3} but similar wavefront coding methods can be used. We compare four systems obtained with these different wavefront coding methods, via an MTFs equalization optimization criterion.

2. DESCRIPTION OF THE STARTING CONVENTIONAL OPTICAL DESIGN

We consider the case of a Petzval optical system, with a focal length of 5.5 mm and an entrance pupil of 4.6 mm. It is used in the Long Wave Infrared (LWIR) spectrum, with a 12 μm pixel sensor (and therefore, a Nyquist frequency of 42 mm^{-1}). Figure 1 shows the Petzval design. There is a plano-convex lens and a total of three aspherical surfaces to achieve MTFs close to the diffraction limit at any field of view (FoV) at the nominal focus position (0 μm). The goal is to increase the DoF to $[-80, 80]$ μm , while it is naturally at about ± 30 μm according to the Rayleigh criterion. To do so, we modify the first optical surface which is the closest surface to the aperture stop. The surface near the stop position modifies the different FoV in the most equivalent way possible.

3. DOF EXTENSION METHODOLOGY

To extend the DoF of the Petzval, we use the Zemax OpticStudio software and a personal merit function (MF). The goal of this MF is to perform “MTFs equalization”, as described in a previous work.⁴

3.1 MTFs equalization in Zemax

Using the Zemax operands (in particular, “MTFT” and “MTFS”), we constrain the sagittal and tangential MTFs for the different FoV. The constraint specifically takes place in three spatial frequencies, which are chosen during the optimization process.

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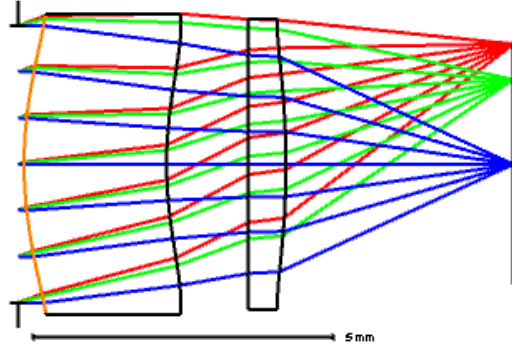


Figure 1. Optical system used for comparison. The orange surface indicates the only modified surface.

3.2 Comparison of four wavefront coding methods

We modify only the first surface of the Petzval in four different ways: 1/ Modification of its aspherical coefficients (order 4 to 8, leaving the curvature radius fixed) 2/ Use of coefficients of type “Generalized cubic phase mask”⁵ (only the curvature radius is maintained, and the polynomials x^3 , x^2y , xy^2 and y^3 are set variables) 3/ Etching of a Diffractive optical element (DOE) (order 2 of a Zemax “BINARY 2” on the aspherical surface) 4/ Etching of 3-rings Binary phase mask, directly on the aspherized surface. The etching of the Binary phase mask was previously determined in a case without aberration.² The other methods for DoF extension are optimized using the MTFs equalization method. It enables to obtain Fig. 2.

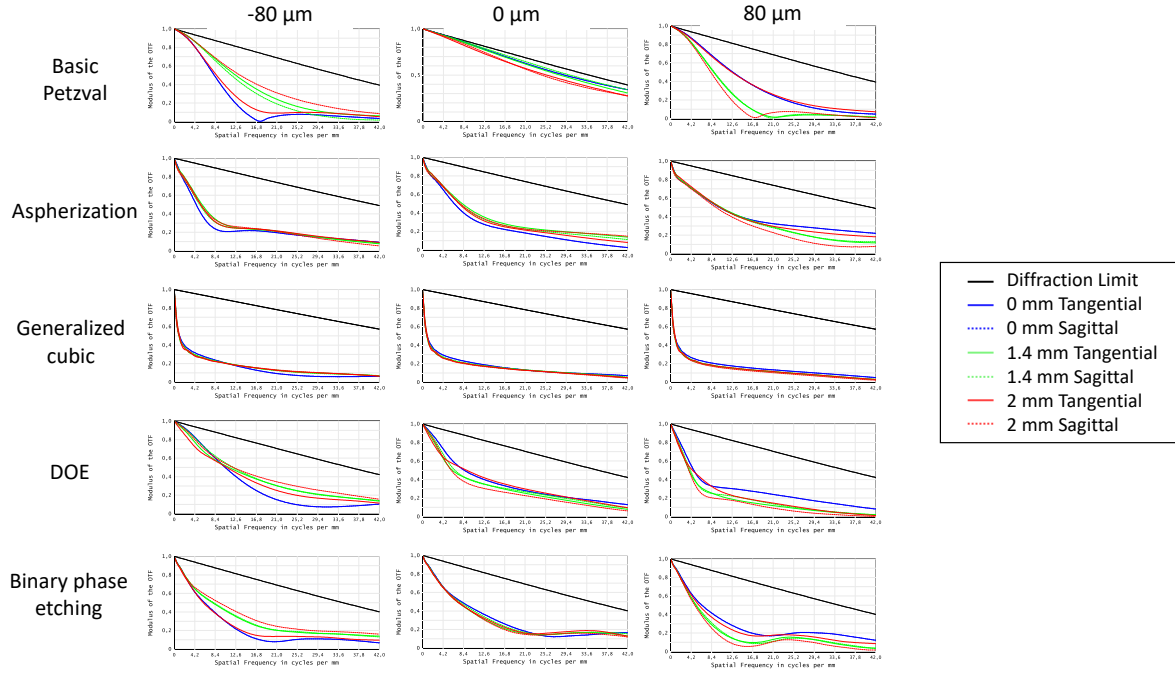


Figure 2. Comparison of the MTFs of the four wavefront coding methods at different DoF.

We can observe that the merit function used effectively equalizes the MTFs in the FoV and the DoF, regardless of the wavefront coding method used. The four methods explored give slightly different results. The importance of these differences on performance criteria which include digital processing has still to be investigated.

4. CONCLUSION

The goal of equalizing MTFs for DoF increase is achieved regardless of the wavefront coding method. This is an encouraging result for DoF extension directly with the modification of an optical surface. Of course, since the MTFs are low for high frequencies, appropriate digital processing will be required.⁶

Furthermore, we can note that these optical systems can be used as interesting starting points for future end-to-end optimization with digital processing. This is indeed a topic that has been addressed for conventional optical systems,⁷ but still little for end-to-end optimized systems.

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