Distributed wavefront coding for wide angle imaging system

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ABSTRACT

The emerging paradigm of imaging systems, known as wavefront coding, which employs joint optimization of both the optical system and the digital post-processing system, has not only increased the degrees of design freedom but also brought several significant system-level benefits. The effectiveness of wavefront coding has been demonstrated by several proof-of-concept systems in the reduction of focus-related aberrations and extension of depth of focus. While previous research on wavefront coding was mainly targeted at imaging systems having a small or modest field of view (FOV), we present a preliminary study on wavefront coding applied to panoramic optical systems. Unlike traditional wavefront coding systems, which only require the constancy of the modulation transfer function (MTF) over an extended focus range, wavefront-coded panoramic systems particularly emphasize the mitigation of significant off-axis aberrations such as field curvature, coma, and astigmatism. The restrictions of using a traditional generalized cubic polynomial pupil phase mask for wide angle systems are studied in this paper. It is shown that a traditional approach can be used when the variation of the off-axis aberrations remains modest. Consequently, we propose to study how a distributed wavefront coding approach, where two surfaces are used for encoding the wavefront, can be applied to wide angle lenses. A few cases designed using Zemax are presented and discussed

Keywords: Wavefront coding, wide angle, panoramic, phase mask

1. INTRODUCTION

Wavefront coding is a technique developed to enhance the depth of focus of imaging systems[1] but it can also be used to reduce focus-related aberrations[2-4] and ease tolerancing[5 6]. The basic concept of this method is to extend the depth of focus by inserting a phase mask near the system aperture stop. This phase mask degrades the MTF but in a way that it can easily be reconstructed by post-processing. The efficiency of this technique has been shown in theory and real world applications[7 8]. However, the application of this technique to wide angle systems poses some challenges; In order to perform a proper image reconstruction, the PSF must be sufficiently constant over the whole captured image. As the field of view increases, this becomes much more complicated to achieve as some aberrations vary as a function of the field angle. It is nevertheless possible to do wavefront coding by adding an additional surface to the phase mask. This paper shows simulation results for wide angle systems that use this technique. The first part of the paper presents the characteristics of the optics. The original design is detailed and then compared to the wavefront-coded designs. These designs are compared by means of image simulations in the second part of the paper.

2. DESIGN PRESENTATION

2.1 Original design

Here we present the characteristics of the optical design used as a basis for wavefront coding. The system is a wide angle Panomorph[9] lens with a full field of view (FFOV) of 180 degree. The Panomorph lens uses distortion control to produce zones of augmented resolution[9]. Controlling distortion introduces a different aberration-to-field dependence which is not completely understood. Another feature of this design is the anamorphosis introduced in the system. This anamorphosis transforms the circular image usually formed by a fisheye type lens into an elliptical image. This elliptical image more efficiently covers a rectangular sensor and optimizes the number of pixels used. This anamorphosis breaks the circular symmetry of the system. The aberration in the image plane is no longer rotationally symmetric and is now dependent on the azimuthal and radial position of the field on the detector. Figure 1 shows the main characteristics of a Panomorph optic. For simplicity, only the characteristics of the system along the major axis of the imaging ellipse are shown.

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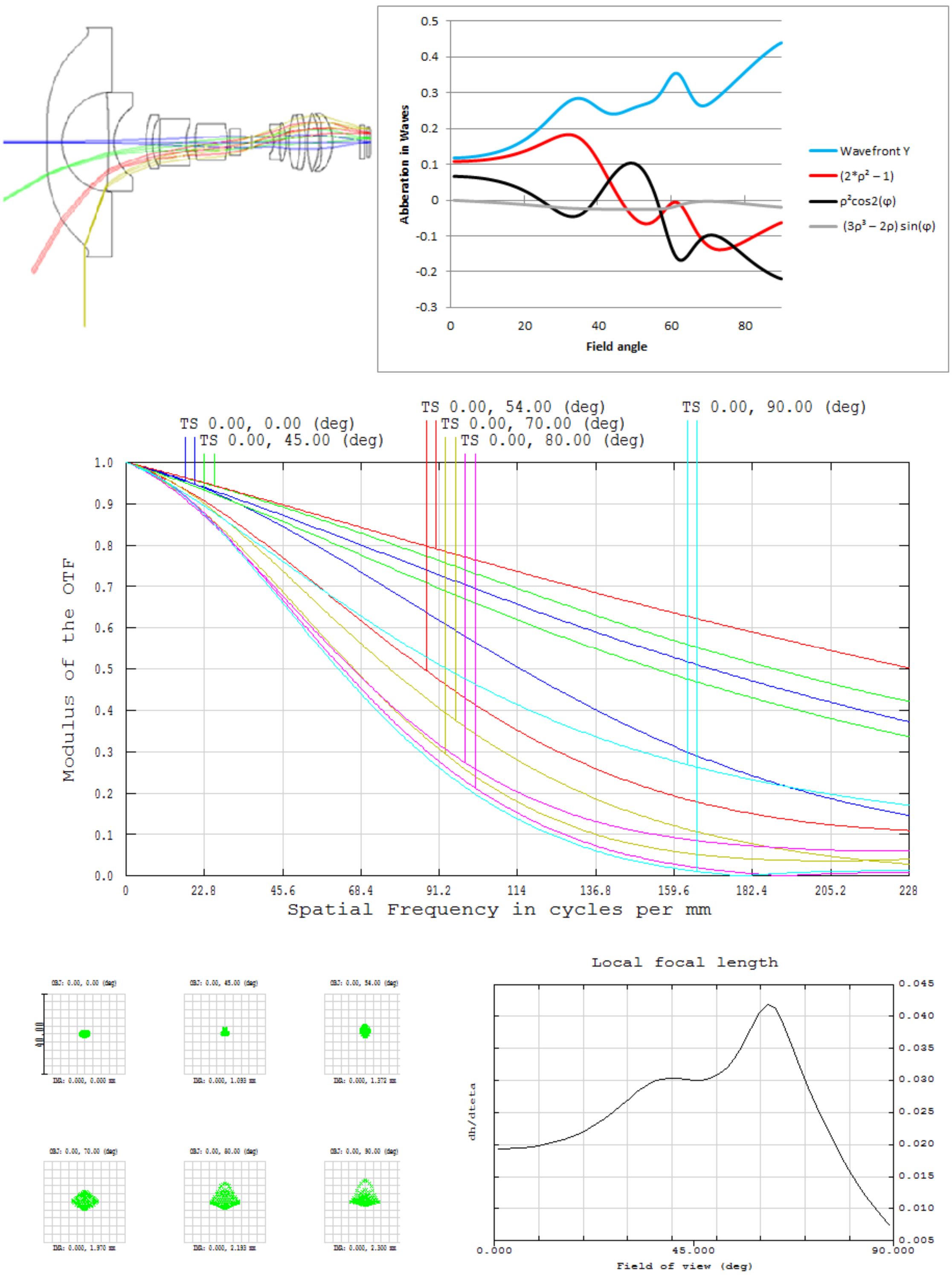

Figure 1: Original system: This image shows the layout of the original system (top left), a plot of the wavefront and the principal Zernike coefficient (normalised with the Zernike fringe coefficient) as a function of the field (top right), The MTF of the system at 587nm for different fields (center), the spot diagram (bottom left) and finally the local focal length as a function of the field position (bottom right)[10].

From analyses depicted in figure 1, the original design shows lots of variation in performance for the different field positions. Two factors contribute to this variation: the wide field of view and the distortion control. Since neither of these factors can be reduced, the encoding of the system wavefront must mitigate these differences between the field angles in order to benefit from deconvolution.

2.2 Phase mask

In this section we see what happens when we try to put a phase mask in the stop of the system and optimize it to obtain an MTF as constant as possible. The phase function of the mask is chosen to be

$$Phase = A \cdot x^3 + B \cdot y^3 + C \cdot xy^2 + D \cdot x^2 y \quad (1)$$

This is similar to a cubic phase mask but has been extended with additional cross term and a different constant for the primary terms. The motivation for the use of this phase function is the particular symmetry of the original design. Considering the fact that we lack the circular symmetry it is possible that a particular orientation requires a stronger phase variation in order to reduce aberrations in this direction. The optimization of the phase mask is made, with the rest of the system parameters kept constant (except for focus). The resulting optimized system characteristics are presented in the following figures.

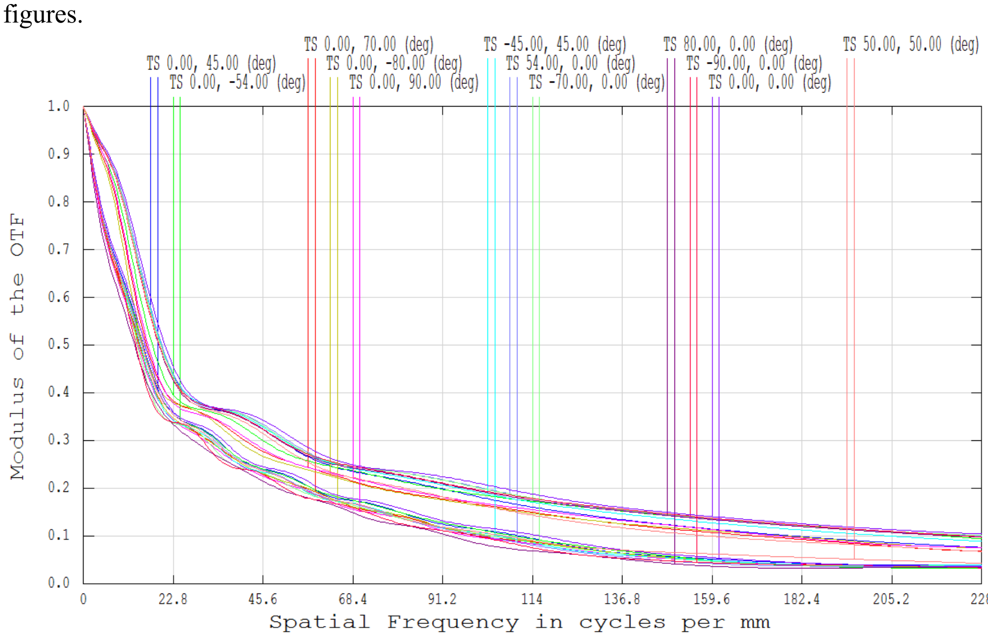

Figure 3: Tangential and sagittal MTF of the system with an extended cubic phase mask at 587nm for multiple field angles

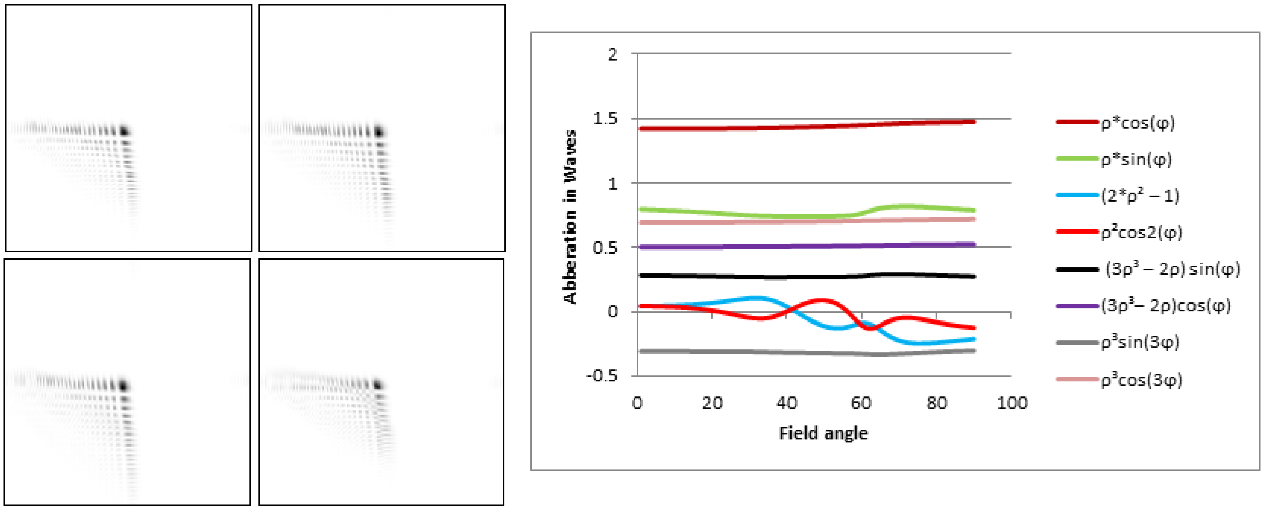

Figure 4: Selected PSF and graphic of aberrations for the system with an extended cubic phase mask

As expected, the system is much more constant. It should be noted that on figure 3 the tangential and sagittal MTF are separated for each FOV. It seems that the cubic phase mask has affected the tangential and sagittal fields differently. The phase mask has essentially introduced a high level constant aberration (as a function of the field of view). This has made the PSF similar over the whole image but some variations still occur. In order to reduce the artefact in the deconvolution process, the PSF must be as identical as possible (simulation results are shown in section 3). To achieve this, we propose a novel distributed wavefront coding approach.

2.3 Distributed wavefront coding

Distributed wavefront coding refers to the use of another surface in the optical layout to further encode the system. The constraints on the design limit the choice of such a surface. Distortion control gives a tight constraint on the first element because most of the distortion comes from that element. Therefore, the front element cannot be used for encoding. Furthermore any freeform surface close to the front element risks affecting the distortion. Also, surfaces that are near the stop cannot affect the field independently and will be redundant with the standard phase mask approach. Therefore, only the very few last surfaces of the system can be modified. These surfaces can affect the field independently and reduce aberrations, like coma, that affects the performance of the system with a phase mask. The chosen surface in this case is the very last surface of the system and it is transformed from a spherical into an extended aspheric surface. Optimization is made using the same merit function as the design with only a phase mask. A summary of the distributed wavefront-coded system properties is presented in the following figures.

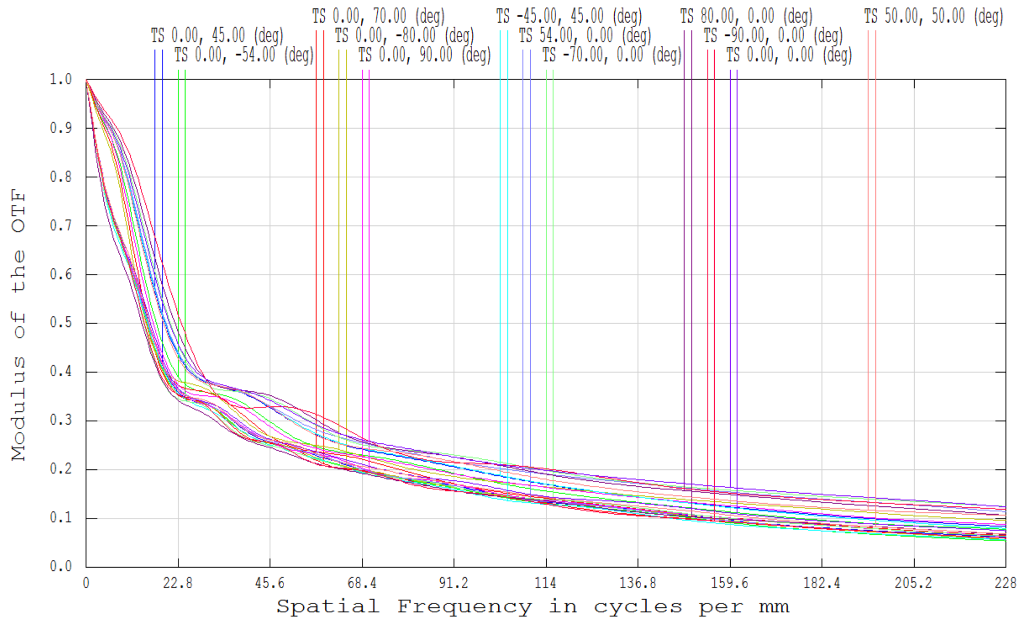

Figure 5: MTF of the system with an extended cubic phase mask and an added aspheric surface at 587nm

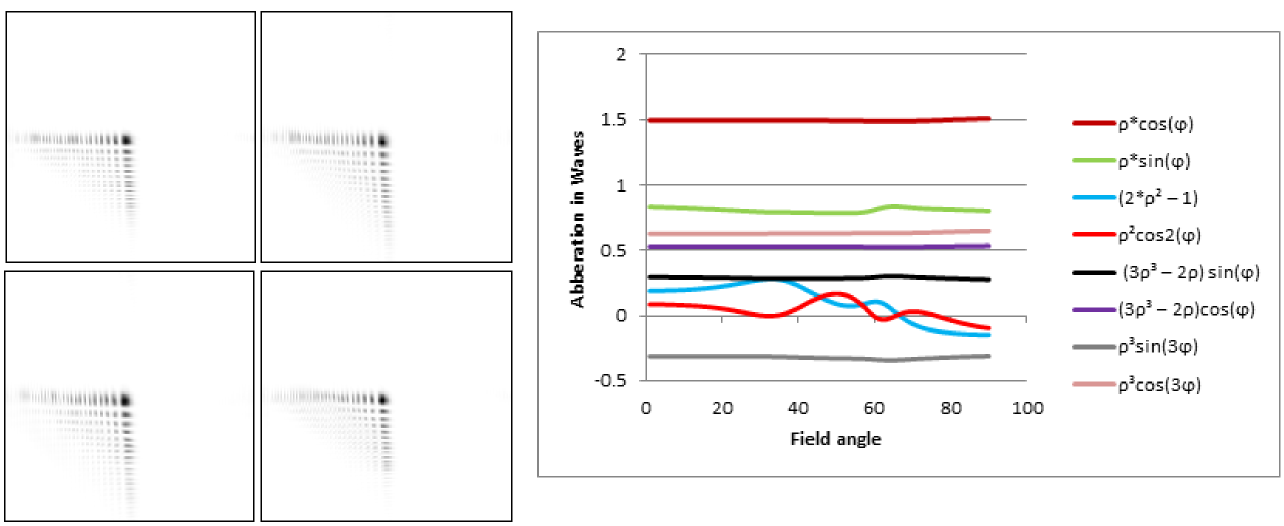

Figure 6: Selected PSF (same as fig. 4) and graphic of aberration for the system with an extended cubic phase mask and an added aspheric surface.

The MTF and the PSF of the system are slightly more constant across the field while maintaining its extended depth of field properties. The tangential and sagittal MTF are now closer to each other. Some aberrations have been affected by a constant amount but the more important variation in the encoding is too subtle to be seen on those images. However, if we plot the variation of the coma ($(3\rho^3 - 2\rho)\sin(\varphi)$) from its mean value, we can make an interesting observation.

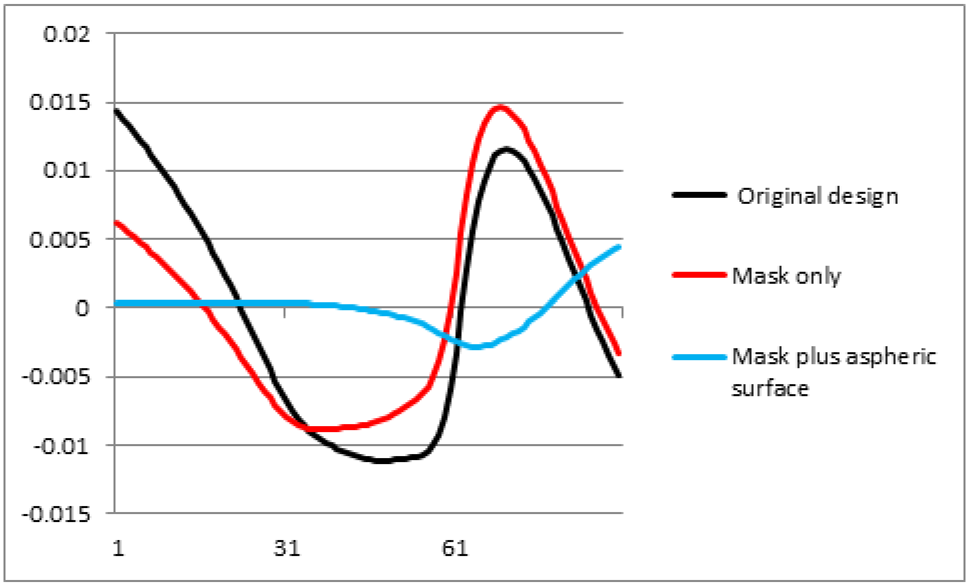

Figure 7: Variation of the $(3\rho^3 - 2\rho^2)\cdot\sin(\varphi)$ coma term from its mean value for the three designs.

The coma aberration has been flattened by the last aspheric surface. Interestingly, if we look at figure 6, we can see that the field curvature ($2\rho^2$-1) and the astigmatism (ρ^2*cos(2φ)) are not smoother than in the original design. Since the phase mask has increased the depth of focus of the optics there was little advantage to reduce the field curve or astigmatism. But coma is not related to focus so its variation can affect the PSF more strongly.

After the optimization, it is important to verify if the system still meets the original requirements. Since no consideration has been given to distortion in the optimization process, the distortion profile may be affected by the addition of an aspheric surface in the optical design. To verify that the distortion profile is not changed, we perform a comparison of the local focal length[10].

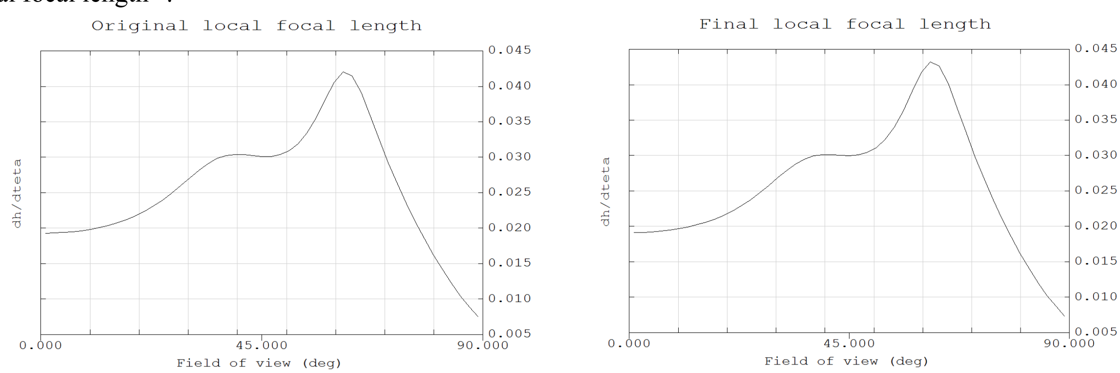

Figure 8: Local focal length of the original design (left) and of the wavefront-coded design with aspheric surface (right)

The local focal length profile of the optimized distributed coding system has a small variation from the original system. Nevertheless the distortion profile was not affected significantly. This is because the position of the modified surface within the system has been specifically chosen to avoid major change in distortion.

3. RESULTS

In order to compare the imaging quality of the different optical systems, image simulations have been carried out to compare image restoration processing of the two wavefront-coded systems and the original system. The image used is the spokes target. For the original system, the image has been convolved with the PSF at different field angles. The same procedure was applied to the designs with wavefront coding but with the addition of a deconvolution with their respective central PSF (at 0 degree field angle).

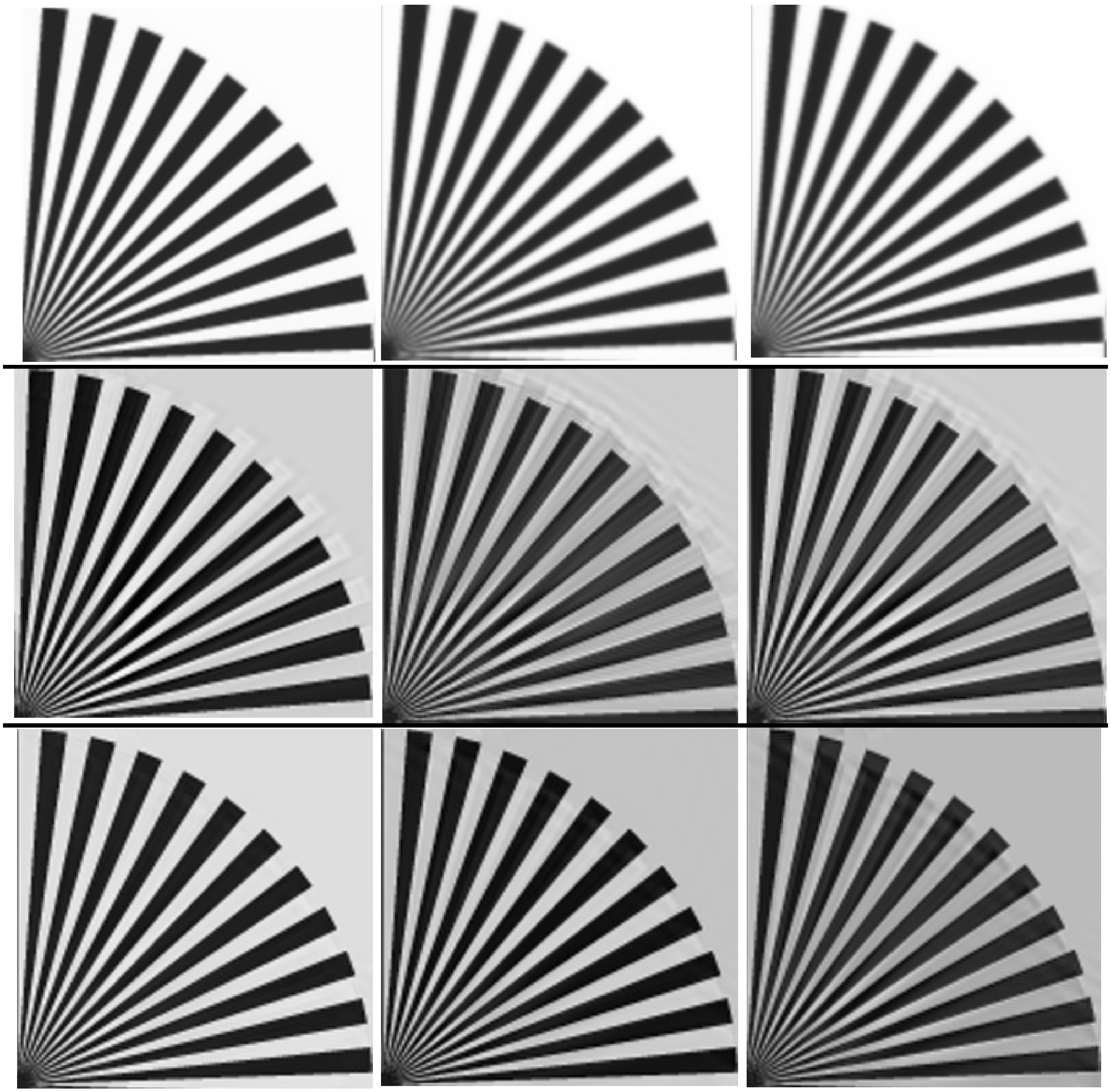

Figure 9: Image simulation for the three systems: the first row show simulation for the original system at three different fields, the second row show the simulation for the second system (phase mask only) and the third for the last system (phase mask plus aspheric last surface) all for the same field and wavelength (587nm).

Since the original system is well corrected there is little room for improvement. The sharpness is nevertheless slightly increased which indicates that the effects of astigmatism and field curve are reduced. The improvements are, however, minor for both designs. The design with traditional wavefront coding shows significantly more artefact than the design with distributed wavefront coding. This can be attributed to the fact that the system having the modified last surface imaging properties are more constant over the whole field of view.

4. CONCLUSION

In this paper we demonstrated the applicability of wavefront coding to a panoramic system. With the insertion of an extended cubic phase mask in the stop of the system the PSF becomes sufficiently constant across the field of view to allow reconstruction using deconvolution. With the increased depth of focus generated, the impact of focus related aberration is reduced and tolerancing becomes easier. However, some artefacts appear in the final image due to small differences in the PSF at different field angles. To reduce those artefacts, we added an aspheric surface far from the stop. When optimized correctly, the added aspheric surface can render a more uniform PSF over the whole FOV and reduce artefact in the image restoration process. This aspheric surface is used to reduce the aberrations that are the most detrimental to the image processing restoration. Results presented in this paper are preliminary and the optimisations were performed only on the MTF. The next step to apply wavefront coding to a panoramic imager is to identify how much of each aberration the system can tolerate and use this information during the optimization. It will then be possible to design panoramic systems with less constraints and better performances by the use of wavefront coding. Future work will also include different types of phase masks in order to see if a specific type of phase mask is more suited for a particular type of aberration or system.

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