# A New Paradigm for Imaging Systems

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## Abstract

Today's imaging systems today frequently have digital components, and some image processing is done in the camera. The potential for dramatically increased performance is not realized, however, until the *complete* imaging system, including the optics and signal processing, is designed as a coherent whole. In such a system, the optics produces an intermediate image, and the final image is produced by signal processing. By designing an integrated optical/digital imaging system, one can use completely different aberration balancing to achieve performance that otherwise would be impossible. Modification of the optics makes it possible to compensate for all focus-related aberrations with signal processing. This frees the optics to compensate optimally for the other aberrations. The result can be high-performance, single-element lenses, or even two-element zoom lenses. Alternatively, if the optics alone corrects for all aberrations adequately, then the depth of field of the imaging system can be dramatically extended. An example is a 10X increase in the depth of field of a microscope.

## Hybrid Optical/Digital Imaging

The new design paradigm requires a modification of the optics to "code" the wave in the aperture stop or an image of the aperture stop. The coding produces an "intermediate" image formed by the optical portion of the system that gathers the image. Signal processing is then required to "decode" the intermediate image to produce a final image. The coding can be designed to make the imaging system invariant to focus-related aberrations. For example, these new focus-invariant imaging systems can have more than an order of magnitude increase in the depth of field. This new paradigm for design of imaging systems has been termed Wavefront Coding. Wavefront Coded optical systems are arrived at by designing the coding optics and the signal processing as an integrated imaging system. Coding of signals to optimally convey particular information is not new. In radar, the pulses are coded to optimally provide information concerning a target's range, for example.

Brenner, Lohmann, and Ojeda-Castañeda showed that a tool that is useful in the design of radar signals, Woodward's ambiguity function, is also useful in examining the Optical Transfer Function (OTF) of an imaging system.[1] Using this technique, it was shown that certain phase plates extend the depth of focus of a hybrid imaging system.[2] A phase plate with the shape

$$z = \alpha (x^3 + y^3) \tag{1}$$

is used to modify the rays as shown in Figs. 1 and 2. Note that the modified rays do not focus as in the case of a normal lens, but form an extended bundle in the region of the image plane. The two-dimensional PSFs are shown in Fig. 3. The PSFs for the traditional system change dramatically with misfocus, but those of the wavefront-coded system do not. The corresponding Modulation Transfer Functions (MTFs) for the wavefront-coded system also change very little with misfocus. In addition, there are no nulls in those MTFs. This allows the use of a single digital filter to process the intermediate image to acquire the final image. Figure 4 shows the traditional image and the wavefront-coded final image of a bar pattern that is tilted at $60^0$. The trace shows that the image formed with the traditional system goes so far out of focus that there is a contrast reversal. The contrast of the image formed with the hybrid optical/digital system stays in focus over the entire region.

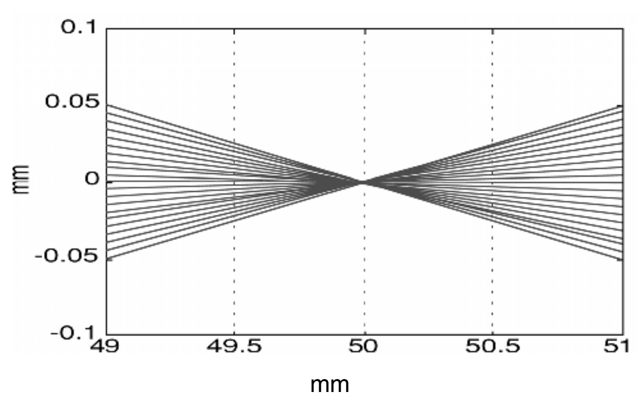



*Figure 1. Normally focussing rays*

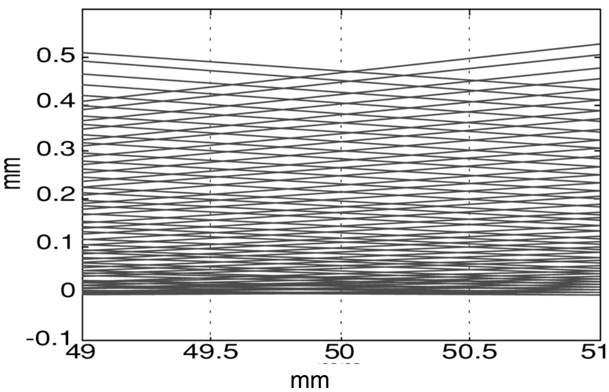



*Figure 2. Rays After the Function of Fig. 1 is Applied*

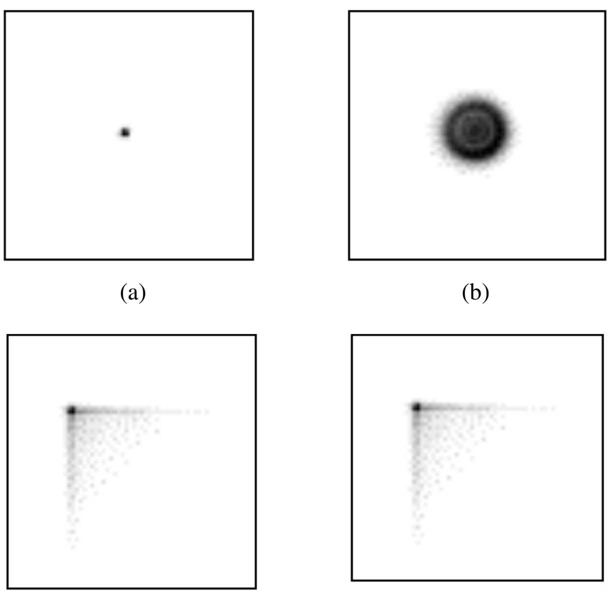
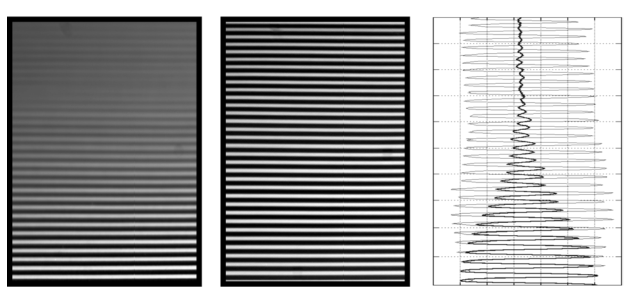


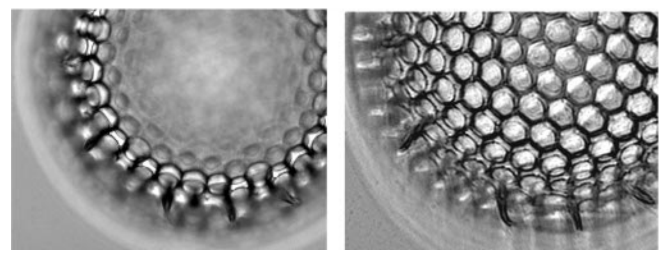

*Figure 3. The PSF of the traditional imaging systems (a) in focus and (b) out of focus, and the system with an extended depth of field (c) and (d) for the same focus settings.*



*(a) (b) (c)*

*Figure 4. Images of a bar pattern tilted at $60^0$. (a) image from a traditional system, (b) image from a hybrid optical/digital system, (c) traces through the images.*

Figure 5 illustrates the power of the technique. The images shown are microscope images of a diatom at 100X magnification. The first image (a) is with a traditional microscope. The second one uses wavefront coding on a phase plate in a slider position to extend the depth of field by about 10 times. This technique allows the user to view entire cells at high magnification, rather than seeing only a small portion of the image. This is especially important with live cells that are moving, with time, in and out of the focal plane of the microscope.



*(a) (b)*

*Figure 5. Microscope image of a diatom at 100/X using (a) a traditional system, (b) wavefront-coded system*

Figures 4 and 5 illustrate the use of an increase in the depth of focus to increase the depth of field. The increase in the depth of focus can be used in other ways, however. For example, in Petzval curvature or curvature of field, the image focuses on a curved surface, not a plane. If the depth of focus is extended, then instead of a thin curved region of focus, there is a thick curved region of focus that allows a flat detector array to be used. Consequently, the imaging system is insensitive to Petzval curvature. In a similar manner, the imaging system can be made to be insensitive to astigmatism, and chromatic aberration. Figures 6 and 7 show images taken with a two-singlet imaging system. A two-singlet system normally has extreme chromatic aberration. That is, different colors focus in different locations. With the use of wavefront coding to extend the depth of focus, there is a region where the foci for each color overlap, thereby making the imaging system invariant to chromatic aberration. The images of Figs. 6 and 7 are of an Air Force resolution chart. The images of Fig. 6 were formed with the two-singlet traditional system, and those of Fig. 7 were formed using extended depth of focus to make that system invariant to chromatic aberration. The traditional image was focussed on the blue. The upper left image shows the composite red/blue/green image. The upper right image shows the red image that was taken in the optimum focal position for the blue image. The lower left image is the green image that was taken in the optimum focal position for the blue image. Finally, the lower right image is the blue image in its best focus. When wavefront coding is used to extend the depth of focus, the optimal focal positions of the red and green are extended enough to overlap the region of best focus for blue. Consequently, after signal processing to do the decoding, all colors are in focus. There is some residual lateral chromatic aberration (caused by variations in magnification with wavelength); the technique can not make the imaging insensitive to lateral chromatic aberration.

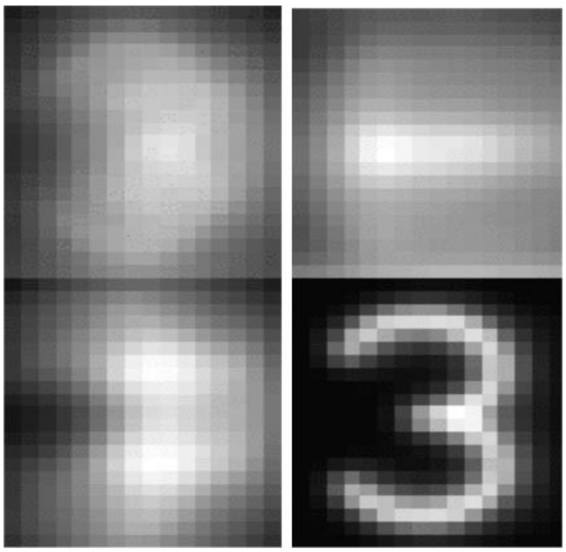


*Figure 6. Using a traditional system, the composite RGB image, the red image, the green, and blue images of the small "3" in an Air Force resolution test chart.*

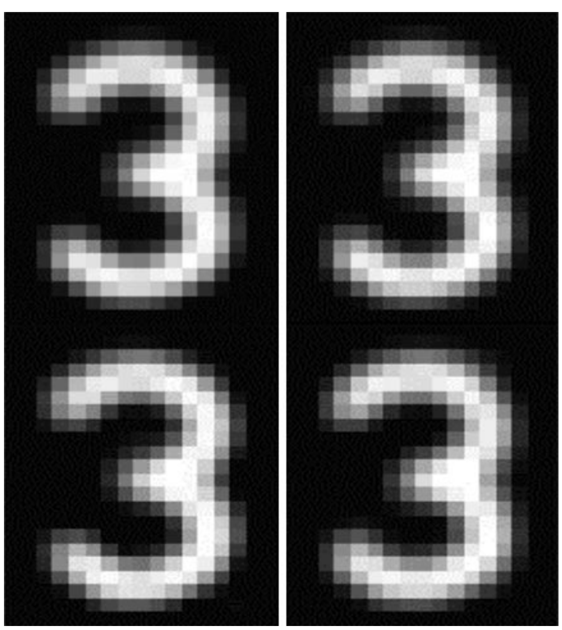


*Figure 7. Using a wavefront-coded system, the composite RGB image, the red image, the green, and blue images of the small "3" in an Air Force resolution test chart.*

By extending the depth of focus with wavefront coding, one can design imaging systems with fewer optical elements, leading to greatly reduced costs. Figure 8 shows a schematic of a fast, single-lens imaging system (with an IR filter and cover plate for the CCD array) that uses the new paradigm. In this example, wavefront coding was used to compensate for focus-related aberrations, and the shape of the lens was used to compensate for distortion and coma. This single-element lens has a field of view of ±30$^{0}$. It also has a large depth of field.

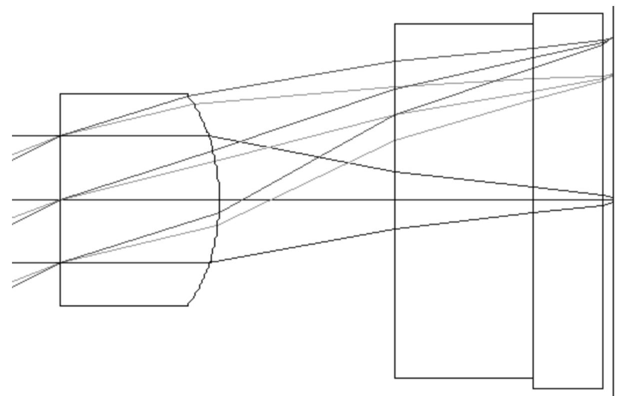


*Figure 8. A single-element lens with high quality imaging and ±30$^{0}$ field of view.*

The modulation transfer functions for the combined optical/digital system using a singlet are shown in Fig. 9. The four lower curves are the MTFs of the intermediate image for objects on axis, at full field, and at 1.5 feet, and infinity. The upper curves are for the final image. They are terminated at the Nyquist limit for the system. These show that the transfer functions on axis, at the edge of the field, and at two object distances are essentially the same. The long line in the upper set is the diffraction-limited MTF including the effect of the pixel size.

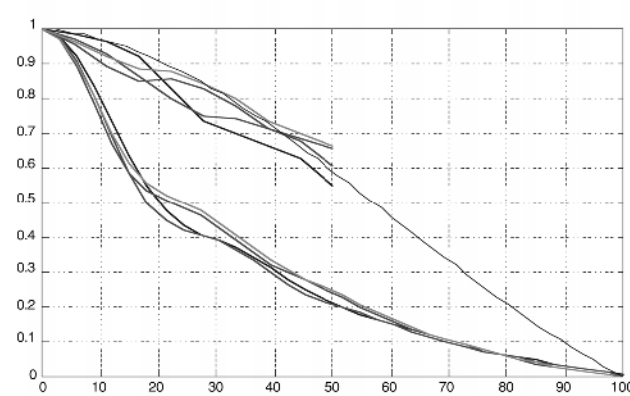



*Figure 9. The MTF curves showing the characteristics of an imaging system on axis, at full field, and for object distances of 1.5 feet and infinity for (a) lower curves giving the performance of the intermediate image and (b) the upper curves giving the performance of the final image.*

## Conclusions

We described the use of a special optical element to modify the optical system to code the image and signal processing to decode the resulting image. By doing this, new performance characteristics of an imaging system can be obtained. The examples given here use the technique of wavefront coding to extend the depth of focus of the imaging system. This increase in depth of focus can be used to increase the depth of field of an existing high quality imaging system such as a microscope. Alternatively, we showed that imaging systems with fewer optical elements can be designed if wavefront coding and signal processing is used. The example given is a single-element plastic lens with good imaging characteristics and wide field of view.

## References

1. K-H. Brenner, A. Lohmann, and J. Ojeda- Castañeda, *The Ambiguity Function as a Polar Display of the OTF,* Optics Communications **44,** 323 (1983).
2. E. R. Dowski and W. T. Cathey, *Extended Depth of Field Through Wavefront Coding,* Applied Optics **34**, 1859 (1995).

## Biography

While teaching and performing research as a regular faculty member for 30 years at the University of Colorado, Dr. Cathey served as Director of the NSF Engineering Research Center for Optoelectronic Computing Systems at the Boulder campus, and as chair of the Electrical Engineering & Computer Science at the Denver Campus. Dr. Cathey now is a Research Professor at the University of Colorado at Boulder, and President of CDM Optics.