# DIGITAL IMAGE PROCESSING FOR PRE-COMPENSATION OF HIGH-ORDER ABERRATIONS OF THE HUMAN EYE

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point spread function, optical transfer function, retina, deconvolution, pre-deblurring, deblurring

## ABSTRACT

Human beings rely significantly on their visual capabilities to successfully interact with their environment. In today's technology-based world, one of the most important interaction channels is through computers. Some individuals with severe visual impairments may have difficulty in interacting with computers, even when using traditional means of visual correction (e.g., spectacles, contact lenses). This is, in part, because these correction mechanisms can only compensate for the most regular distortions or aberrations of the image in the eye. This paper proposes an image processing approach that will pre-compensate the images displayed on the computer screen, so as to counter the effect of the eye's aberrations on the image. The characterization of the eye required to perform this customized pre-compensation is the eye's Point Spread Function (PSF). The PSF can now be measured by a new generation of ophthalmic instruments generically called "Wavefront Analyzers." The characterization provided by these instruments also includes the "higher-order aberration components" and could, therefore, lead to a more comprehensive vision correction than traditional mechanisms. The methods presented here will be explained in terms of their theoretical foundation and illustrated with results from the correction of aberrations introduced by lenses with known and constant PSFs.

## 1 INTRODUCTION

Visual perception is the primary source of information about the surrounding environment that humans have. Through the evolutionary process, humans have developed a very refined sense of vision, seeing in three dimensions with high resolution and color [1]. The sense of sight is so important that, when limited by age or disease, it limits a person's ability to perform otherwise ordinary tasks, such as interacting with a computer system.

Visual perception of objects in the physical world is determined by the formation of their images on the retina, located inside the human eye [2]. However, the natural visual system of some individuals does not accurately map images from the outside world onto their retinas. The most common of these visual impairments include myopia, hyperopia, and astigmatism. All of them result in a retinal representation of a point of light that is not confined to a single point on the retina. The distortion in the mapping of external images onto the retina is represented by the eye's "wavefront aberration function." Myopia, hyperopia, and astigmatism are referred to as low-order aberrations because the distortion they introduce can be modeled by first or second order Zernike polynomials. Currently, spectacles or contact lenses correct these low-order impairments by modifying external images before they reach the eye.

There are cases, however, in which the low-order Zernike model is not sufficient to describe the aberration of the eye. With the recent advances in Wavefront Sensing technology, it is now feasible to accurately model the high-order aberrations present in each person's eye and thus obtain good models of various aberrations currently not correctable through conventional means (e.g., spectacles, contact lenses). Using these models, it would be possible to provide persons with currently uncorrectable aberrations, a new alternative to enhance their interaction with computers.

In contrast with the optical correction of visual limitations, the approach described here is based on modifying the image at its source, i.e., in applying image processing modifications on the image to be displayed on-screen before it is shown to the user, using the knowledge of his/her wavefront aberration function. The aim of the pre-compensation proposed is to modify the intended display image in a way that is opposite to the effect of the wavefront aberration of the eye. Once this is achieved, the result is displayed to the viewer so that the effect of the wavefront aberration in the viewer's eye will "cancel" our pre-compensation resulting in the projection of an undistorted version of the intended image on the retina.

# 2 METHODS

## 2.1 Wavefront aberration and Zernike model

It should be noted that, even if the focusing elements of the eye were perfect, i.e., if there were no aberrations present to distort the image, the retinal image would still contain degradation due to the diffraction of light as it passes through the pupil (diffraction limited) [2]. For a perfectly round pupil, the diffraction pattern of a point source of light appears as a bright spot in the center of the retina, surrounded by faint concentric rings. This is known as the Airy disk [3].

If diffraction is neglected, the light from a point source that enters an ideal eye, free of aberrations, will converge to a focal point on the retina [3].

## 2.2 Imaging in the Human Eye as a Convolution Process

A recent shift in the interpretation of optics has been in the characterization of optical systems, including the human eye, as linear, shift invariant systems described by their point spread function (PSF) [2]. Therefore, the eye can be characterized by its PSF, T(x, y), and the retinal image, R(x, y), can be found by convolving (denoted by $\otimes$) the input to the system, the image of the object to be seen, I(x, y), with the PSF of the eye:

$$R(x,y) = I(x,y) \otimes T(x,y) \qquad (1)$$

When viewing a computer screen, the real world image, I(x, y), is stored as a digital image, DI(x, y), which will be displayed to the user. The retinal image, in this case, will be formed by convolution of the on-screen image and the PSF of the viewer's eye:

$$R(x,y) = DI(x,y) \otimes T(x,y) \qquad (2)$$

In this case, however, the on-screen image to be displayed to the user can be manipulated in advance. If the inverse PSF of the viewer's eye, $T^{-1}$(x, y), could be defined, then an image, RD(x,y), which is the result of convolving the intended digital image, DI(x, y), with this inverse function could be shown to the viewer:

$$RD(x,y) = DI(x,y) \otimes T^{-1}(x,y) \qquad (3)$$

Under these circumstances, substituting the ordinary DI(x,y) with the pre-compensated RD(x,y), in (2):

$$R(x,y) = \{DI(x,y) \otimes T^{-1}(x,y)\} \otimes T(x,y) = DI(x,y) \quad (4)$$

This means that the user would perceive in R(x,y) an undistorted version of the intended digital image, DI(x,y). The image represented by the braces in (4) can also be considered to be the result of deconvolving the PSF, T(x,y), from the intended image, DI(x,y). This is the pre-compensated image to be displayed to the viewer. In practice, the deconvolution process may be performed more efficiently in the frequency domain, as discussed below. In any case, it is clear that, in order to obtain RD(x, y), the PSF of the eye must be known or estimated.

### 2.3 Evaluation of the PSF of the Human Eye

The PSF of the human eye can be found indirectly through what is known as the wavefront aberration function, W(x, y). This function represents the deviation of the light wavefront from a purely spherical pattern as it passes the pupil on its way to the retina [3]. In an unaberrated eye, the refracted light is organized in the form of a uniform spherical wavefront, converging to the paraxial focal point on the retina.

Recently developed "Wavefront Analyzers" based on the Hartmann-Shack Principle have made it possible to measure the wavefront aberration function for the human eye. The wavefront aberration function, W(x,y), is the primary component of the pupil function, P(x,y). The pupil function incorporates the complete information about the imaging properties of the optical system [4]. The pupil function is given by the following:

$$P(x,y) = A(x,y)e^{-j\cdot 2\cdot \pi \cdot n\cdot W(x,y)} \qquad (5)$$

where A(x,y) is the amplitude function describing the relative efficiency of light passing through the pupil (usually given a value of one), n is the index of refraction [3].

According to the Fourier optics relationships in the eye, knowledge of the pupil function can be used to determine the optical transfer function, OTF, which is "one of the most powerful descriptors of imaging performance for an optical system" [3]. The OTF is a complex function whose magnitude is the modulation transfer function (MTF) and whose phase is the phase transfer function (PTF) [3].

The OTF can be found by convolving the pupil function, P(x,y), with its complex conjugate, P*(-x,-y) [2],[3]:

$$O(fx, fy) = P(x,y) \otimes P^*(-x,-y) \qquad (6)$$

which is equivalent of saying that the OTF is the autocorrelation of the pupil function. The PSF and the OTF are a Fourier transform pair [5]:

$$O(fx, fy) = F\{T(x,y)\} \qquad (7)$$

### 2.4 Zernike Polynomials

The Zernike polynomials are two-dimensional functions that form a complete orthogonal basis set defined on the unit disc. They have been used in optical engineering for over 60 years, [6], [7], [8]. Recently, the Zernike polynomials have been applied to the characterization of aberrations of the human eye [9], [10], [11]. Modern ophthalmic wavefront analyzers provide an approximation to the wavefront aberration function measured from the subject as a combination of Zernike polynomials. As indicated by equations (5), (6), and (7), this characterization of the optics of the eye can be used to determine its PSF and OTF, thus enabling the implementation of the deconvolution concept expressed in equations (3) and (4), as detailed below.

### 2.5 Inverse Filtering

Inverse filtering is traditionally used in image processing to restore an image U(x,y) from a degraded image G(x,y), assuming a known degradation function, H(x,y). As stated above, the input and output of any linear system are related through the convolution operator. That is,

$$G(x,y) = U(x,y) \otimes H(x,y) \qquad (8)$$

If the Fourier principles of convolution are applied, U(x,y) can be obtained as follows:

$$U(x,y) = F^{-1}\left\{\frac{F\{G(x,y)\}}{F\{H(x,y)\}}\right\} \qquad (9)$$

where $F\{\ \}$ and $F^{-1}\{\ \}$ denote the Fourier transform and the inverse Fourier transform, respectively.

In the context of pre-compensation of a digital image to be shown to the viewer, the objective is to deconvolve the PSF of the viewer's eye, T(x, y), from the intended digital image, DI(x, y), in order to derive the pre-compensated display image to show on-screen, RD(x, y). Making the corresponding substitutions in equation (9), the calculation of RD(x, y) is practically accomplished as:

$$RD(x,y) = F^{-1}\left\{\frac{F\{DI(x,y)\}}{F\{T(x,y)\}}\right\} \qquad (10)$$

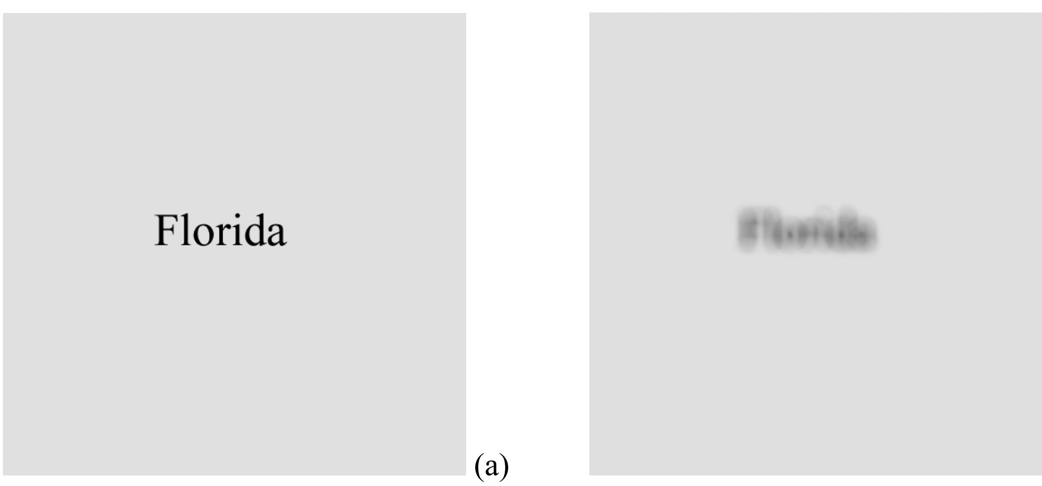
This process is commonly known as inverse filtering in frequency, with its correlation in space being deconvolution. It should be noted that, according to equation (7), the denominator within the braces of equation (10) is the OTF of the viewer's eye.

But this implementation of inverse filtering has several limitations, especially for values of the PSF or its frequency counterpart, the OTF, which are close to zero. A common approach to circumvent this problem is the use of Minimum Mean Square Error filtering [12]. In the context of the problem at hand, this approach obtains the pre-compensated image as:

$$RD(fx,fy) = \left[\frac{1}{T(fx,fy)}\frac{|T(fx,fy)|^2}{|T(fx,fy)|^2 + K}\right]DI(fx,fy) \qquad (11)$$

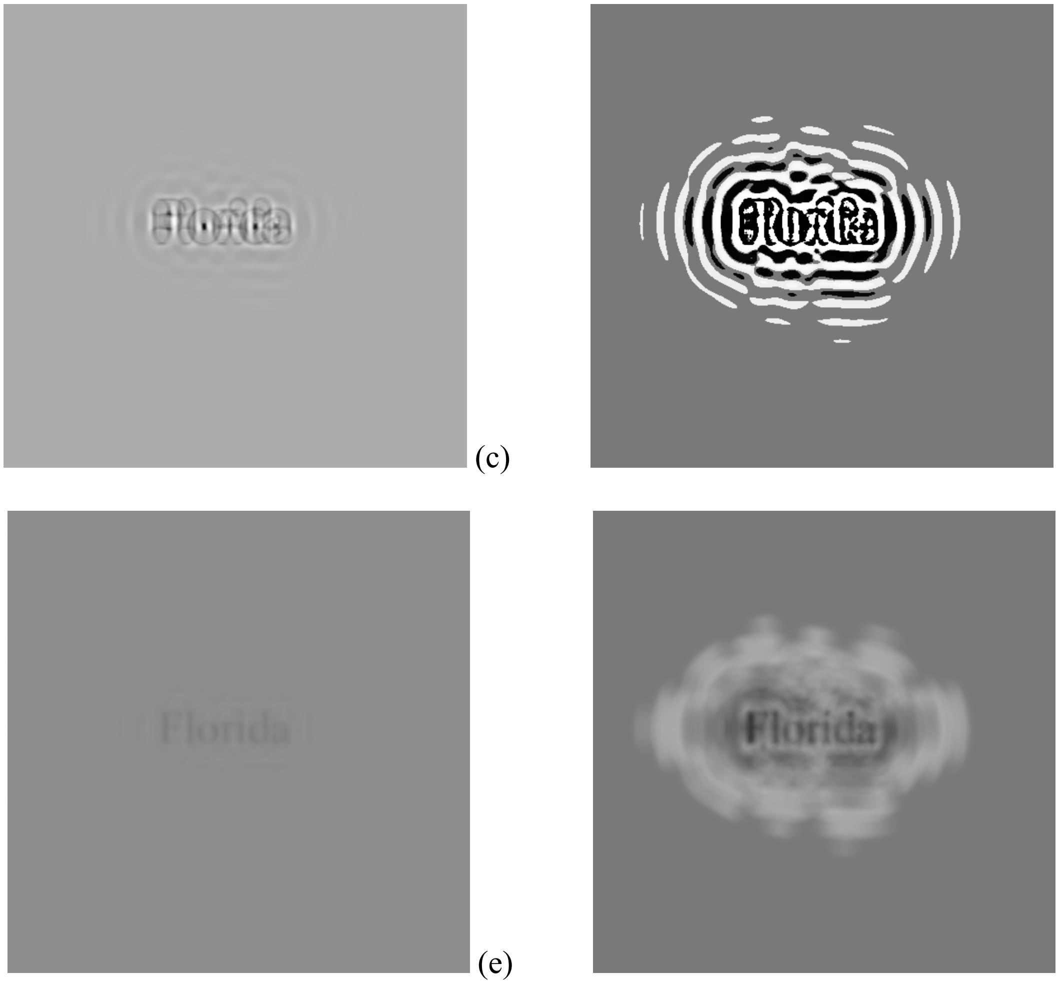
where RD(fx,fy), T(fx,fy), and DI(fx,fy) are the Fourier transforms of RD(x,y), T(x,y), and DI(x,y), respectively. In addition to the limitation of values in the pre-compensated image, the approach indicated in equation (11) helps reduce the impact of modeling or measurement noise inherent to the definition of the eye's PSF. The K factor in equation (11) should be proportional to the magnitude of the estimation noise in the PSF approximation.

## RESULTS




(a) (b)

Figure 1




(c) (d) (e) (f)

Figure 1-continued (a) Original Image, DI(x,y) (b) Retinal Image seen with uncorrected vision, R(x,y) (c) Pre -deblurred Image, RD(x,y) (d) Pre-deblurred with histogram equalization ( to increase contrast), RD(x,y) (e) Image “c” seen through aberration, R(x,y) (f) Image “d” seen through aberration, R(x,y)

## DISCUSSION

The images in Figure 1 were generated using MATLAB, incorporating the pupil function, equation (5). Image (a), is the image (512 x 512 pixels) as it is intended to be viewed by the person upon application of the pre-compensation. Image (b) is the retinal image, through a 3.25 diopter defocus with a 4mm pupil size seen from a distance of 2.5 meters( under indoor lighting conditions, the pupil is approximately 4mm in diameter [13]). Under these conditions, the image subtends 2.32˚ of visual angle. In order to perform the processing, the sampling frequency of the image must match that of the eye. The sampling frequency of the eye was found to be 6319.12 cycles per radian. In order to match the sampling frequency of the eye, the viewing distance must be 2.5 meters. When the 512x512 image is viewed on a monitor (40.8cm x 30.6cm) with a resolution of 1024x768 at a distance of 2.5 meters, the effective spatial sampling rate, in cycles per radian, is 6319.1. Image (c) and (d) are the results of pre-compensation, one image as generated (Figure 1 c) and the other has been post-processed through histogram equalization (Figure 1 d). Figure 1 (e) and (f) are the resulting retinal images perceived by the subject seeing the images, (c) and (d), through the specified aberration. Notice the improvement in the image with the histogram equalization.

## CONCLUSIONS

This paper has proposed a framework for inverse-filtering images before they are displayed to low-vision users on a computer screen in order to compensate for their visual limitations. The results shown in Figure 1 reveal the entire process for a visually limited eye. The model is for an eye with a pupil diameter of 4mm and a 3.25 diopter defocus. The images, 512 x 512 pixels displayed on a 40 x 30 cm monitor with a resolution of 1024 x 768, subtends 2.32˚ when viewed at 2.5 meters. Although this example pre-compensates for a simple blur, it should be noted that this framework also contemplates the correction of higher-order optical aberrations that are not addressed by current visual correction methods.

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