Effects of Aberrations on the Point Spread Function of a Three Zone Aberrated Optical Imaging System with Variable Apodization

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Abstract—The presence of optical aberrations degrades the performance of an optical system. These effects can be reduced by inserting proper amplitude filters. In the current study, suitable amplitude-apodization pupils have been used for tailoring the point spread function (PSF), in order to attain full-width at half-maximum (FWHM) and suppressed side lobes. Intensity profiles for the unapodized and variable apodized cases have been considered. By comparing and analyzing various PSFs, the effects induced by monochromatic aberrations such as the defocusing effect, and primary spherical aberration have been controlled for various degrees of apodization parameter β. The proposed apodizer is very effective in increasing the resolution of optical systems.

Keywords: Apodization; point spread function; two-point resolution

The main physical significance of PSF is to obtain output of an optical system for any input by applying the convolution operation of a given input. From the knowledge of the PSF of the system the resolution of an optical system can be judged. A suitable aperture of shading is very helpful to correct the Seidel aberration effect in the image plane of the optical system.

There have been a number of studies involving apodization for different aberration considerations [1-10]. An aberrated optical system results in the PSF with non-zero first minima, enhanced side lobes due to the displacement of internal energy of the central lobe, widened central lobe, and shifted first minima positions, which represent the fundamental problem in aberrated optical systems [6]. The apertures with different transmission functions play a vital role in modifying the point spread function (PSF) in numerous applications. Recently, many studies have drawn attention to developing this property [9]. Based on the investigations done in the three zone apodization process, it can be inferred that symmetric apodization was introduced, namely a Triangular filter in the inner zone, Connes filter in the middle zone, and the Hanning amplitude filter in the outer zone could be the solution in increasing the intensity as well as suppression of side lobes of the optical system under the strong combined influence of defocus and primary spherical aberration.

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The proposed amplitude apodization in improving the two-point resolution of the aberrated optical system is important in astronomical observations. In the present study, we introduce a flexible apodization technique to transform the distorted intensity PSF into a smooth intensity PSF, which also resolves the two-point resolution problem of the aberrated optical system illuminated by light with different coherence conditions.

The expression for diffraction field of three amplitude filters is given by:

$$\begin{aligned}S(\emptyset_d,\emptyset_s,Z) = {} & 2\int_0^a f_1(x)\exp\left[-i\left(\emptyset_d\frac{x^2}{2}+\frac{1}{4}\emptyset_s x^4\right)\right]J_0(Zx)x\,dx \\ & + 2\int_a^b f_2(x)\exp\left[-i\left(\emptyset_d\frac{x^2}{2}+\frac{1}{4}\emptyset_s x^4\right)\right]J_0(Zx)x\,dx \\ & + 2\int_b^1 f_3(x)\exp\left[-i\left(\emptyset_d\frac{x^2}{2}+\frac{1}{4}\emptyset_s x^4\right)\right]J_0(Zx)x\,dx\end{aligned} \quad (1)$$

where $f_1(x)$ is the triangular amplitude pupil function, $f_2(x)$ is the Connes amplitude pupil function, $f_3(x)$ is the Hanning amplitude pupil function of the optical system; Z is the dimension less variable, which forms the distance of the point of investigation from the center of the diffraction field; and $J_0(Z_x)$ is the zero order Bessel function of the first kind; 'x' is the reduced radial coordinate on the exit-pupil of an aberrations-influenced optical system.

The coefficient $\emptyset_s$ is the amount of primary spherical aberration. The coefficient $\emptyset_d$ is the amount of defocus aberration. For the calculation of intensity response, the amount of aberration is expressed in terms of dimensionless quantities π/2, π, 3π/2 and 2π. In the current study, the pupil functions we have considered are Triangular, Connes and Hanning filter of second order respectively, which can be represented by:

$$f_1(x) = (1-\beta x) \qquad \text{(Triangular filter)} \quad (2)$$
$$f_2(x) = (1-\beta^2x^2)^2 \qquad \text{(Connes filter)} \quad (3)$$
$$f_3(x) = cos(\pi\beta x) \qquad \text{(Hanning filter)} \quad (4)$$

where β is the apodization coefficient, which controls the degree of apodization.

The intensity PSF $B(Z)$ which is the measurable quantity can be obtained by taking the squared modulus of S(Z). Thus,

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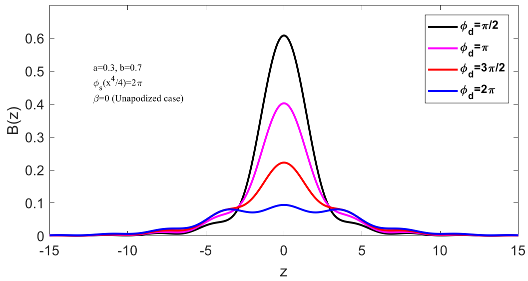
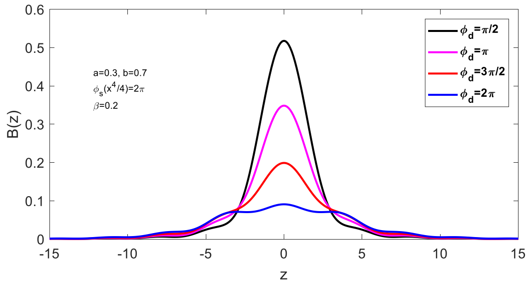
$$B(Z) = |S(Z)|^2. \tag{5}$$

Figures 1(a), 1(b), 1(c) shows that in the presence of high primary spherical aberration ($\emptyset_s = 2\pi$) as the amount of defocusing effect ($\emptyset_d$) increases, the internal energy of the central peak is displaced, resulting in the enhanced side lobe region for β = 0, 0.2, 0.4, respectively.

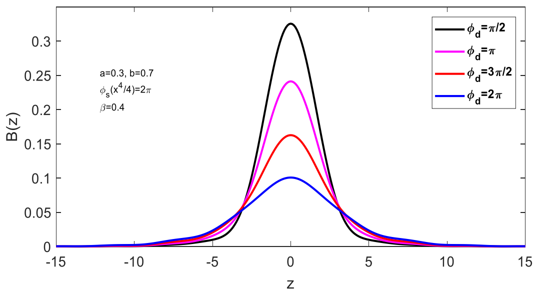
(a)



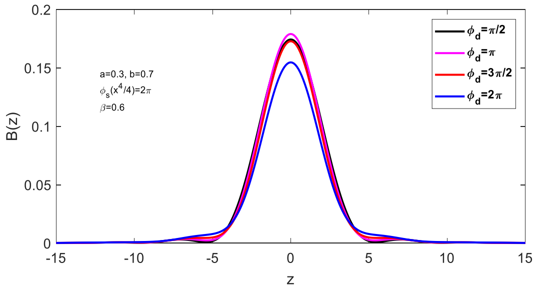
(b)



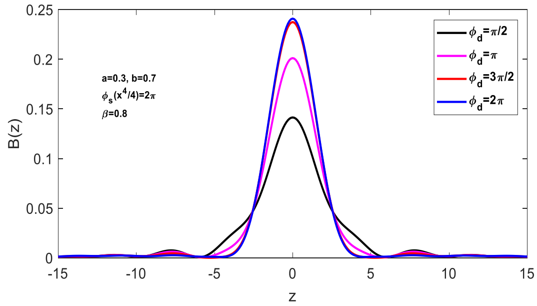
(c)



(d)



(e)



(f)

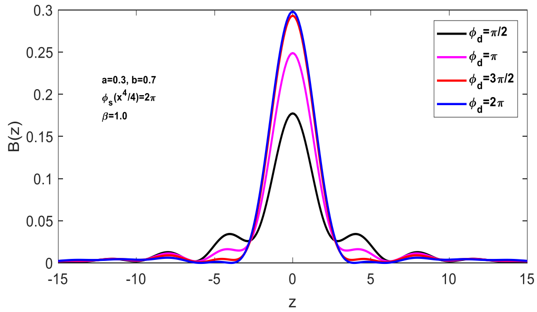
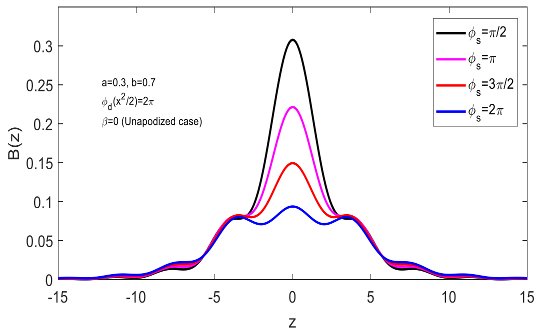


Fig. 1. PSF Intensity profiles under high spherical aberration with different amount of defocusing aberration from (a) unapodized pupil (β = 0) to (f) apodized pupil (β = 1).

When β = 0.6 (see Fig. 1 (d)), β = 0.8 (see Fig. 1 (e)) and β = 1.0 (see Fig. 1 (f)), the resulting PSF intensity distribution in different defocussed planes ($\emptyset_d = 2\pi$) shows that even in the presence of a high amount of monochromatic aberrations, the employed apodization across the pupil increased intensity distribution and suppressed the side lobes, resulting in smooth intensity PSFs.

From Fig. 2(a) for unapodized pupil β=0, at higher order defocussed planes ($\emptyset_d = 2\pi$), it is found that the intensity decreases and side lobes are increased with an increase in the primary spherical aberration values ranging from π/2 to 2π, thus indicating the presence of non-zero first minima.

(a)



(b)

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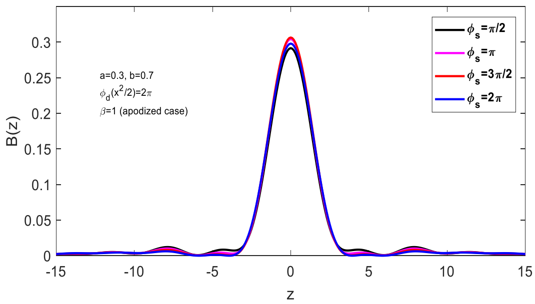

Fig. 2. PSF intensity profiles for different values of spherical aberration in a highly defocussed plane $\emptyset_d = 2\pi$: (a) unapodized pupil (β = 0) and (b) apodized pupil (β = 1).

From Fig. 2(b) for apodized pupil β=*1*, at higher order defocussed planes ($\emptyset_d = 2\pi$), it is found that the intensity increases and side lobes are completely suppressed with an increase in the primary spherical aberration values ranging from π/2 to 2π, thus resulting in the elimination of non-zero first minima.

Table 1. Positions and intensities of the maxima minima of the aberrated PSFs for various β values.

β	c. max		f. min	
	position	value	position	value
0.0	0	0.094	2.0176	0.0713
0.2	0	0.0909	2.3623	0.0705
0.4	0	0.1008	--	--
0.6	0	0.1548	--	--
0.8	0	0.2409	4.6805	0.0009
1.0	**0**	**0.298**	**3.9282**	**0.0000**

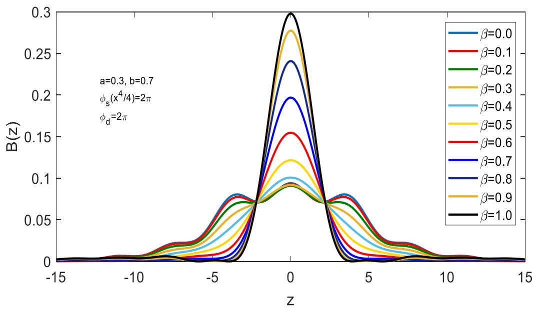

Fig. 3. The impact of apodization on the intensity profile PSF when the defocussing effect ($\emptyset_d$= 2π) and the spherical aberration ($\emptyset_s$ = 2π) are high.

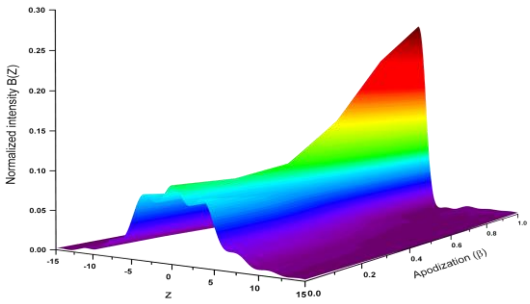

Fig. 4. 3D intensity profiles in the presence of high primary spherical aberration ($\emptyset_s$ = 2π) and defocussing effect ($\emptyset_d$= 2π) for different levels of pupil aopdization from (β=0 to β=1).

In conclusions, from Table 1 and Figures 3–4, it is evident that the apodization pupil (β = 1) is efficient in improving the performance of aberrated optical systems relatively with the apodization pupils (β = 0.2, 0.4, 0.6 and 0.8). It is shown that the proposed apodizer greatly improves the performance of three zone aberrated optical systems by increasing the intensity and suppressing the side lobes for higher degrees of defocus and primary spherical aberration when three amplitude filters: i.e., triangular, Connes and Hanning, are employed in the inner, middle and outer zone, respectively, which helps in designing optical instruments that are used in microscopy, astronomical telescopes and also beam focusing systems.

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