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Truncated Pupils In The Reduction Of Optical Side-Lobes Of Point Spread Function

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Abstract: *In this study, we present efficient truncated apertures for modulating the Point Spread Function (PSF) of an optical system. The selected amount of apodization, along with the value of the truncated parameter, has demonstrated significant improvements in the resolution of the optical system compared to clear circular apertures. Through careful optimization of the apodization process, we were able to tailor the PSF intensity distribution, leading to increased resolution. These findings have promising implications for enhancing image quality and resolving finer details in various imaging applications.*

Key words: *Point Spread Function (PSF), truncated apertures, Optical system, Apodization, optical side lobes, Resolution, Image quality.*

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I. Introduction

The Point Spread Function (PSF) is a fundamental concept in optics and imaging, describing the response of an optical system to a point source of light. In astronomy, astronomers use different aperture transmission functions to tailor the PSF for specific tasks, such as enhancing spatial resolution, reducing chromatic aberration, minimizing diffraction effects, or optimizing the sensitivity to faint celestial objects.[1-11]. To achieve improved PSF intensity distributions we can employ various techniques, including pupil engineering (e.g., apodization, truncation, and aberration correction), adaptive optics, and computational deconvolution methods. There was already a significant amount of research focused on developing and optimizing the properties of Point Spread Functions (PSFs) for various applications. The enhancement of the first minima and the changes in the PSF due to aberrations has practical implications for image quality and resolution in optical systems [1-3]. Apodization filtering is an important technique in optical systems, helping to eliminate the effects of various optical aberrations and improving image quality [1-4][9-10]. The truncated apodizers involves carefully tailoring the amplitude or phase of the light passing through the aperture of the optical system. This modification of the optical intensity distribution helps to shape the PSF according to the desired specifications. Truncated apodizers are a powerful tool in optical engineering, enabling the customization of the PSF to enhance the performance of aberrated optical systems and improve image quality.

II. Theory

The amplitude Point Spread Function (PSF) for a Gaussian focal plane, which describes the diffraction pattern or the light intensity distribution at the focal spot of an optical system, can be given by the square modulus of the Fourier Transform of the aperture function. For a circular aperture, this results in a well-known expression known as the Airy disk pattern.

$$G_F(0,\quad Z) = 2\int_0^1 f(r)\ J_0(Zr)rdr \qquad (1)$$

Where *f(r)* is the Gaussian type apodization function, Z - is the reduced dimensionless diffraction coordinate, J_0 - the zero-order Bessel function of the first kind and the parameter ‘r’ is the polarizer radial coordinator.

The expression for amplitude point spread function of the optical system suffering from defect of focus for complex pupil function of two-zone aperture can be written as

$$G_F(\phi_d,\ Z) = [2\int_0^a f_1(r)\exp\left[-i\left(\frac{1}{2}\phi_d r^2\right)\right] J_0(Zr)rdr - \frac{\pi}{3}\int_a^1 f_2(r)\exp\left[-i\left(\frac{1}{2}\phi_d r^2\right)\right] J_0(Zr)rdr] \qquad (2)$$

Where ϕ_d is the defocusing

The expression to compute the intensity distribution in the image plane for a point objects using the complex pupil functions with truncated by circular apertures can be described by:

$$B_F(\phi_d, Z) = \left[2\int_0^a f_1(r)\exp\left[-i\left(\frac{1}{2}\phi_d r^2\right)\right] J_0(Zr)rdr \; - \frac{\pi}{3}\int_a^s f_2(r)\exp\left[-i\left(\frac{1}{2}\phi_d r^2\right)\right] J_0(Zr)rdr \right]^2 \quad (3)$$

$$f(r) = Cos(\pi \beta r) \qquad \text{[Hanning amplitude filter]} \qquad (4)$$

$$f(r) = (1 - \beta r^2)^2 \qquad \text{[Straubel amplitude filter]} \qquad (5)$$

$$f(r) = \frac{(1 + \beta \cos(\pi r^2))}{1 + \beta} \qquad \text{[Cosinusoidal amplitude filter]} \qquad (6)$$

Where $f(r) =$ the pupil functions

$\beta =$ The apodization parameter

$r =$ Normalized distance of the point on the pupil from the centre

III. Results and discussion

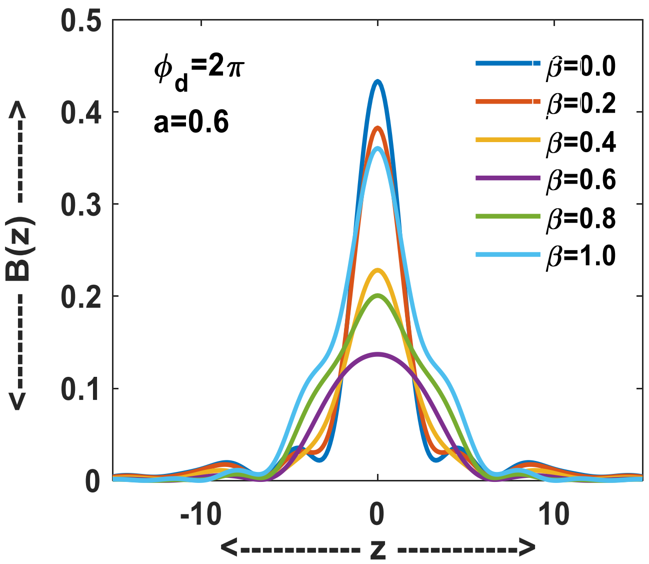

Figure.1

Figure 1 shows the intensity distribution curves of an optical system apodized with a complex pupil function for the clear circular aperture. In this configuration, the inner zone is apodized with a Cosinusoidal amplitude filter, while the outer zone is apodized with a Hanning amplitude filter. The central zone parameter, "a," is fixed at a value of 0.6. Additionally, the optical system is highly defocused (ϕ_d=2π). As the apodization parameter (β) increases, the intensity in the central lobe decreases, particularly for extreme apodization when compared to the Airy case (β=0). For β=0 that is Airy case, the light flux is shifted into the secondary maxima. Moreover, for highly apodized cases (β=1), there is an increase in the width of the central maximum. In other words, the central peak becomes broader and more spread out compared to the unapodized case or Airy case (β=0).

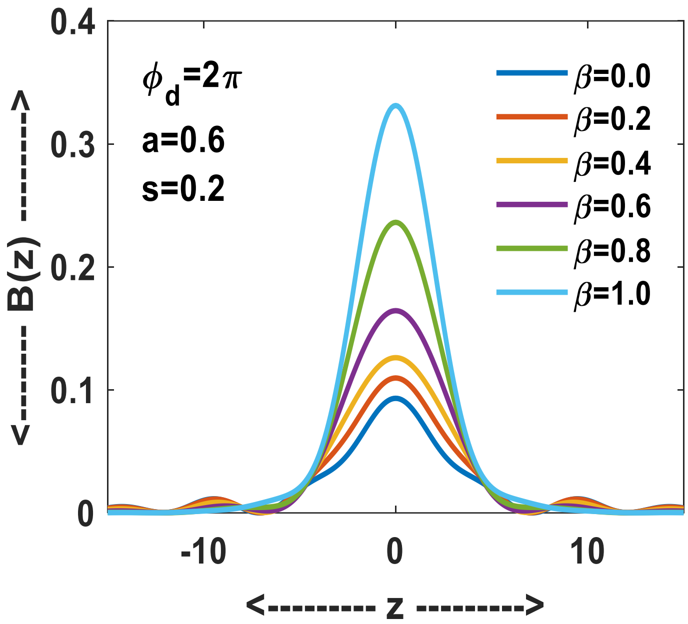

Figure. 2

Fig.2 depicts that the When the optical system is under the influence of truncation, and the apodization process involves the use of a Cosinusoidal amplitude filter for the inner zone and a Hanning amplitude filter for the outer zone. Furthermore, the phase change of (-π/3) is introduced to the complex pupil function. It refers the intensity distribution curves for central zone parameter "a" = 0.6 and truncated parameter s=0.2 the intensity in the central lobe is more pronounced for highly apodized optical system, and the optical side lobes are completely suppressed. Therefore the chosen truncated filters are more effective in shaping the diffraction pattern. As a result, the Point Spread Function (PSF) obtained exhibits the desired characteristics, with increased intensity in the central irradiance and zero intensity in the first minima for highly apodized case.

Table-1

a=0.6	β	c. max		f. min	
		Pos.	Value	Pos.	Value
φ_d=2π	0	0	0.4332	3.3048	0.0219
	0.1	0	0.4296	3.4034	0.0265
	0.2	0	0.3826	3.6545	0.0304
	0.3	0	0.3081	6.6046	0.0029
	0.4	0	0.2282	6.6302	0.0019
	0.5	0	0.1655	6.6458	0.0012
	0.6	0	0.1370	6.6296	0.0010
	0.7	0	0.1499	6.6153	0.0016
	0.8	0	0.2007	6.6333	0.0029
	0.9	0	0.2767	6.6792	0.0047
	1	0	0.3605	6.7509	0.0066

Table-2

a=0.6/ s=0.2	β	c. max		f. min	
		Pos.	Value	Pos.	Value
φ_d=2π	0	0	0.0932	7.1083	0.0000
	0.1	0	0.1027	7.0701	0.0001
	0.2	0	0.1097	7.0129	0.0001
	0.3	0	0.1166	6.9348	0.0002
	0.4	0	0.1262	6.8391	0.0004
	0.5	0	0.1414	6.7419	0.0008
	0.6	0	0.1644	6.6774	0.0016
	0.7	0	0.1962	6.7102	0.0029
	0.8	0	0.2362	12.1720	0.0001
	0.9	0	0.2824	12.3916	0.0001
	1	0	0.3312	12.5550	0.0001

Table-1 and Table-2 Provides the intensity of the intensity values of the central maxima and the optical side lobes for an optical system under different levels of apodization The apodization is achieved using a cosinusoidal filter in the inner zone and a Hanning filter in the outer zone with a phase difference of $-\pi/3$ and the optical system is highly defocused.

Table-1provides the intensity in the central maxima and first minima tables for the clear circular aperture. From the table.1 it can be observed that, as the level of apodization increases (β increases from 0 to 1), the intensity at the central maximum decreases. In the Airy case (β=0), the intensity at the central maximum is 0.4332, and in the case of extreme apodization (β=1), the intensity at the central maximum is 0.3605. This indicates that apodization reduces the intensity of the central peak. Despite the decrease in the intensity of the central maximum, the first minima or optical side lobes are not minimized. The side lobes may still have significant intensity, even with increased apodization.

Table-2, depict the intensity values of the central maximum and the optical side lobes for an optical system with a truncated aperture under different levels of apodization. The parameter β controls the level of apodization, where β=0 corresponds to no apodization (Airy case) and β=1 corresponds to extreme apodization. As the level of apodization increases (β increases from 0 to 1), the intensity of the central lobe increases significantly. In the unapodized or Airy case (β=0), the value of the central maximum is 0.0932, in the apodized optical system (β=1), the central maximum is 0.3312, which is about 3.5 times greater than the Airy case, this indicates that apodization has effectively improved the intensity of the central peak. However, when the aperture is truncated (Table-2 shows the results for the truncated aperture), the first minimum is reduced to 0.0001 under extreme apodization. This indicates that truncation can have a significant effect on the suppression of optical side lobes, and extreme apodization further improves this suppression**.**

IV. Concussions

In the present study the truncated circular apertures with a highly defocused optical system provide significant improvements in highly intense central peaks and complete suppression of optical side lobes, which results in tailored Point Spread Function. These findings offer promising opportunities for optimizing optical system performance and achieving superior image quality in diverse imaging applications.

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