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Variable Apodization Effects on the Point Spread Function of a Four-Zone Aperture in the Presence of Optical Aberrations

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Abstract. *There are two significant merit function of PSF, the first one being the intensity in the central lobe of the PSF should be large and the second being the width of the central maximum or the radius of the first dark ring in the PSF should be less when compared to that of the Airy case. The focus of this work is to formulate the optical filters so that the two aspects of the merit features of the PSF are realized in terms of reduction in the first minima and increase in the intensity distribution in the central maxima.*
This article presents a comprehensive study on enhancing the resolution of an optical system in the presence of higher-order defocus and primary spherical aberration. The research focuses on introducing four-level variable filters, specifically Triangular, Connes, Polynomial, and Hanning, to improve the system's performance. The investigation involves testing four-zone aperture shading amplitude in each zone to determine the optimal configuration. The results show that placing the Triangular filter in the inner zone, Connes filter in the second zone, Polynomial filter in the third zone, and Hanning filter in the outer zone yields the best outcome. This specific arrangement enables the optical system to achieve a super-resolver state, even in the presence of high degrees of defocusing and primary spherical aberration. The study demonstrates that the highest degree of amplitude apodization significantly enhances the lateral resolution of the central maxima while suppressing side lobes. This improvement is crucial for studying two-point resolution, a critical aspect of optical imaging. The findings of this research have significant implications for the development of high-performance optical systems.
Key Words: *Point spread function; Defocus; Primary spherical aberration; Super resolution, Apodization*

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I. Introduction:

Imaging systems inherently introduce imperfections, making it impossible to capture an object's exact likeness. The two-dimensional Point Spread Function (PSF) serves as a comprehensive descriptor of an imaging system's resolution, providing a quantitative analysis of image degradation within the system. This function plays a crucial role in assessing an imaging system's suitability for specific tasks, facilitating comparisons between different systems, and potentially restoring subtle image details.

The PSF's significance extends to various applications, including microscopy, astronomy, and medical imaging. By characterizing the PSF, researchers and engineers can develop strategies to mitigate image degradation, ultimately enhancing the overall quality of the captured images. Furthermore, understanding the PSF enables the development of image restoration techniques, which can help recover lost details and improve image clarity.

In addition to the PSF, the Modulation Transfer Function (MTF) provides an alternative framework for characterizing image degradation in the frequency domain. As the Fourier transform of the PSF, the MTF describes how effectively an imaging system transfers spatial information from the object being observed to the captured image. The MTF is a valuable tool for evaluating an imaging system's performance, as it provides a quantitative measure of the system's ability to resolve fine details.

The relationship between the PSF and MTF is fundamental to understanding the underlying mechanisms of image formation and degradation. By analyzing these functions, researchers can identify potential limitations and develop innovative solutions to overcome them. This knowledge can be applied to various fields, from biomedical imaging to astronomical observations, ultimately leading to advancements in our understanding of the world around us.

In conclusion, the Point Spread Function and Modulation Transfer Function are essential concepts in imaging science, providing a framework for understanding and characterizing image degradation. By exploring these functions, researchers can develop new strategies for improving image quality, ultimately driving innovation in various fields and enabling us to capture the world with greater clarity and precision. Optical systems primarily function to form images, either for detection and recording or visual examination. To evaluate image quality, quantitative merit functions are developed, focusing on the system's application. Modern image quality analysis views the image-forming process as a two-stage Fourier transformation, where the object and image are perceived as 2D light distributions. When a lens forms an image, the object's light distribution is transformed into the spatial frequency domain, passed through a band-pass filter and transformed back into the linear domain. This framework considers the lens system a low-pass spatial frequency filter, with its effects on image quality specified by a spatial frequency band-pass curve. The application of communication theory to optics led to a qualitative shift in image formation and analysis. Fourier analysis became a mathematical tool in image science, describing image formation in terms of impulse response or system transfer functions. This frequency domain analysis has become a powerful tool for evaluating and describing optical systems. Optical systems can modify aperture diameter and radius of curvature to control light flux and focus, improving image quality to a limited extent. Most optical systems form images for detection, recording, or visual examination. To evaluate image quality, users require application-specific specifications. Image quality analysis develops quantitative merit functions to assess image quality. Modern image quality analysis views image formation as a two-stage Fourier transformation, transforming object distributions into spatial frequency domains and back into linear domains. Lens systems act as low-pass spatial frequency filters, with effects on image quality specified by spatial frequency band-pass curves.

The integration of communication theory and optics has led to the application of Fourier analysis in image science. This approach enables the description of image formation using impulse responses or system transfer functions, facilitating the evaluation of optical systems through frequency domain analysis.

However, achieving a perfect representation of reality through imaging is impossible due to inherent limitations. Noise and blur, resulting from detection processes, focus issues, or optical constraints, inevitably degrade image quality. The Point Spread Function (PSF) plays a critical role in understanding this degradation, as it convolves with the original image to produce the blurred picture detected.

The PSF is influenced by various system parameters and object distances, making it a vital mechanism for studying optical imaging systems. By analyzing the PSF, researchers can gain insights into the limitations and potential improvements of optical imaging systems, ultimately advancing our understanding of image formation and degradation.

In real-time imaging, defocused PSFs are utilized for optical sectioning in microscope image visualization systems. Understanding the PSF is essential for evaluating and improving optical systems, as it accurately measures the blur in an image.

Previous studies have examined the response of defocused optical systems to line frequencies [1], aberration-free defocused optical systems [2], and defocused PSFs and optical transfer functions of microscopes [3]. Additionally, the effects of defocus on the optical transfer function (OTF) have been investigated [4]. To enhance resolution, variable apodization has been introduced, modifying the aperture with amplitude apodization β, considering defocus and primary spherical aberration.

The use of variable filters and amplitude apodization techniques can be applied to various optical imaging applications, including microscopy, astronomy, and biomedical imaging. By pushing the boundaries of optical resolution, this research contributes to the advancement of imaging technologies and opens up new possibilities for scientific exploration and discovery.

By identifying the most effective filter combinations, this study paves the way for the development of high-resolution optical systems capable of producing clearer images despite the presence of aberrations. Investigations suggest that a specific filter combination can modify the PSF: Triangular amplitude filter (0-0.3), Connes amplitude filter (0.3-0.5), Polynomial filter (0.5-0.7), and Hanning amplitude filter (0.7-1). This combination can effectively address defocus and primary spherical aberration, improving the optical system's resolution.

This study investigates the application of various filters and filter combinations to modify the Point Spread Function (PSF). The findings demonstrate that a tailored combination of Triangular, Connes, Polynomial, and Hanning amplitude filters can effectively suppress secondary side-lobes and enhance resolution.

This research makes a significant contribution to the field of PSF resolution, showcasing the potential of optimal filter combinations to modify the PSF and improve resolution in optical systems affected by defocus and primary spherical aberration.

By optimizing the filter configuration and amplitude apodization, researchers and engineers can design systems capable of producing high-resolution images, even in the presence of aberrations. In conclusion, this study showcases the effectiveness of using four-level variable filters and amplitude apodization to enhance the resolution of optical systems. The results provide valuable insights for designing and optimizing high-performance optical imaging systems, ultimately driving innovation in various fields.

II. Theory

This research examined the effects of a four-zone filter with various combinations on an optical system's performance. The optimal configuration was achieved by positioning the Hanning amplitude mask in the outermost zone and strategically interchanging the other three filters. The most effective combination consisted of: Triangular amplitude filter in the first zone, Connes filter in the second zone, Polynomial filter in the third zone and Hanning filter in the outermost zone.

This specific arrangement yielded the best outcome, demonstrating that careful selection and placement of filters can significantly enhance the optical system's performance. By identifying the optimal filter combination, this study provides valuable insights for designing high-performance optical systems.This combination yielded the best results in the presence of defocus and primary spherical aberration. The diffraction field of the four amplitude filters can be expressed mathematically as:

$$S(Z) = 2[\int_0^a (f_1(x) J_0\,(Zx)xdx \int_a^b (f_2(x)\, J_0(Zx)xdx \int_b^c (f_3(x)\, J_0(Zx)xdx + \int_c^1 (f_4(x) J_0\,(Zx)xdx] \quad \textbf{(1)}$$

Where:

- $f_1(x)$ represents the triangular amplitude pupil function
- $f_2(x)$ represents the Connes amplitude pupil function
- $f_3(x)$ represents the Hanning amplitude pupil function of the optical system
- Z is a dimensionless variable indicating the distance from the center of the diffraction field
- $J_0(Zx)$ is the zero-order Bessel function of the first kind
- 'x' is the reduced radial coordinate on the exit-pupil of the aberrations-influenced optical system.

For the defocussed planes ($\emptyset_d$), the amplitude distribution of the four zone PSF is given by

$$S(\emptyset_d, Z) = 2\int_0^a f_1\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2}\right)\right] J_0(Zx)xdx + 2\int_a^b f_2\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2}\right)\right] J_0(Zx)xdx + 2\int_b^c f_3\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2}\right)\right] J_0(Zx)xdx + 2\int_c^1 f_4\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2}\right)\right] J_0(Zx)xdx \quad \textbf{(2)}$$

Upon introducing the primary spherical aberration ($\emptyset_s$), eq. (**2**) becomes

$$S(\emptyset_d, \emptyset_s, Z) = 2\int_0^a f_1\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \frac{1}{4}\emptyset_s x^4\right)\right] J_0(Zx)xdx + 2\int_a^b f_2\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \frac{1}{4}\emptyset_s x^4\right)\right] J_0(Zx)xdx + 2\int_b^c f_3\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \frac{1}{4}\emptyset_s x^4\right)\right] J_0(Zx)xdx + 2\int_c^1 f_4\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \frac{1}{4}\emptyset_s x^4\right)\right] J_0(Zx)xdx \quad \textbf{(3)}$$

The coefficients $\emptyset_s$ and $\emptyset_d$ represent the amounts of primary spherical aberration and defocus aberration, respectively.

To calculate the intensity response, these aberrations are expressed as dimensionless quantities, π and 2π. In this study, we considered four pupil functions:

- Triangular filter, Connes filter, Polynomial filter and Hanning filter of second order

These filters can be mathematically represented as:

$$f_1(x) = (1 - \beta x) \qquad \textbf{(Triangular filter)} \qquad \textbf{(4)}$$

$$f_2(x) = (1 - \beta^2 x^2)^2 \qquad \textbf{(Connes Filter)} \qquad \textbf{(5)}$$

$$f_3(x) = 1 - 4\beta x^2 + 4\beta x^4 \qquad \textbf{(Polynomial Filter)} \qquad \textbf{(6)}$$

$$f_4(x) = cos\,(\pi\beta x) \qquad \textbf{(Hanning Filter)} \qquad \textbf{(7)}$$

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,

$$\boldsymbol{B(Z) = |S(Z)|^2} \qquad \textbf{(8)}$$

III. Experiment & discussions

The amplitude apodizer controls light transmission in the optical system, with pupil transmittance varying with radial coordinate x and apodization coefficient β. Higher β values significantly impact the aberrated system's response, with 90% attenuation of light transmission from pupil edges. This apodization function corrects severe aberration effects, including increased side lobes and displaced internal energy.

Equations (3)-(8) generated point spread functions for apodized apertures with variable apodization using four amplitude filters in Matlab. Figures 2-6 show intensity distribution curves for various apodization parameters with and without defocus and primary spherical aberration (a=0.3, b=0.5, c=0.7) using Triangular, Connes, polynomial, and Hanning filters.

The intensity distribution curves indicate that partial apodization (β = 0.50) eliminates optical side-lobes, shaping the point spread function to the desired profile. Extreme apodization (β = 1) tailors the central lobe, increasing central maximum intensity and reducing full width at half maxima (FWHM). Variable apodization enhances the optical system's performance by reducing aberration effects and improving the point spread function's profile.

Figure 1 and **Table 1** illustrate the impact of apodization parameter β on the intensity distribution of the Point Spread Function (PSF) without defocus and spherical aberration. Increasing β decreases the central lobe's intensity. As β rises from 0 to 0.5, optical side lobes are completely eliminated. However, for higher apodization orders (β=1), the first dark ring's radius in the diffraction pattern becomes smaller than in the **Airy case.**

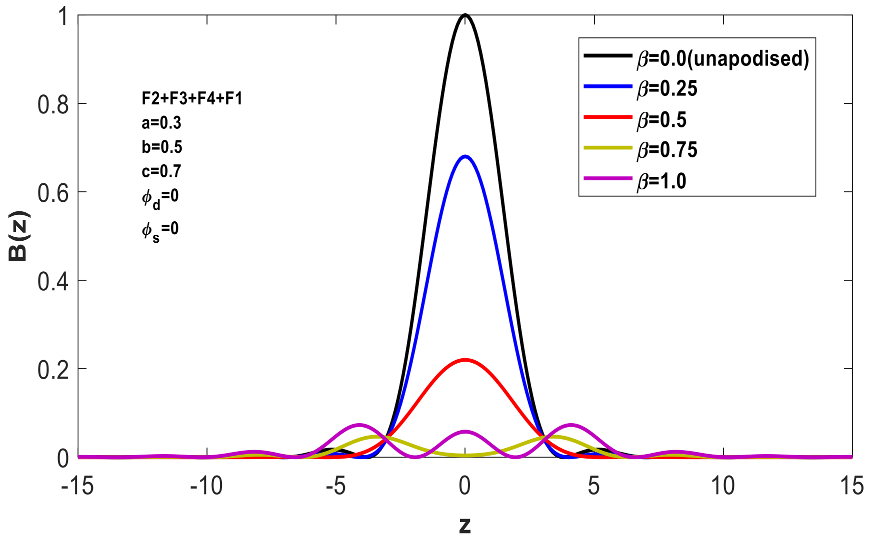

Figure 1. Point Spread Function (PSF) Intensities without Defocus and Spherical Aberration

The table below summarizes the intensities and positions of maxima and minima of the Point Spread Function (PSF) for varying apodization parameters (β) in the absence of defocus and primary spherical aberration:

Table 1. PSF Characteristics without Defocus and Spherical Aberration

		c. max		**f. min**		**f. max**	
	β	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
a=0.3, b=0.5, c=0.7, φd =φs=0	**0**	0	1	3.8317	0	5.1356	0.0175
	0.25	0	0.6802	4.0195	0	5.2449	0.0076
	0.5	0	0.2202	5.3447	0	6.6308	0.0006
	0.75	0	0.0042	3.4205	0.0467	7.9587	0.0056
	1	0	0.0579	1.9442	0	4.1001	0.073

Figure 2 and **Table 2** illustrate the impact of apodization parameter β on the intensity distribution of the Point Spread Function (PSF) in the presence of defocus (ϕd=π) and primary spherical aberration (ϕs=π). Increasing β from 0 to 0.75 decreases the central lobe's intensity. However, at β=1, the intensity increases compared to β=0.5, but side lobes remain unsuppressed.

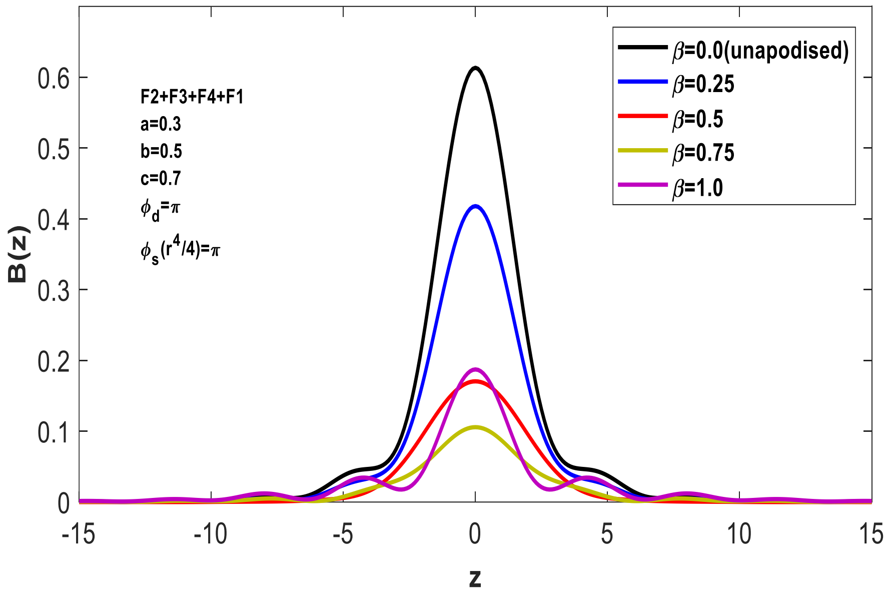

Figure 2. PSF Intensities with Defocus $\phi_d=\pi$ and Spherical Aberration $\phi_s=\pi$ for varying apodization parameters (β)

Table 2. Intensities and positions of maxima and minima of the PSF at defocus $\phi_d=\pi$ and primary spherical aberration $\phi_s=\pi$

		c. max		f. min		f. max	
	β	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
a=0.3, b=0.5, c=0.7, φd=π φs(r^4/4)=π	**0**	0	0.6133	6.9436	0.0057	8.0547	0.0081
	0.25	0	0.4179	6.9599	0.003	8.126	0.0047
	0.5	0	0.1705	11.5163	0	--	--
	0.75	0	0.1057	6.1048	0.0014	7.736	0.0051
	1	0	0.1873	2.8217	0.0177	4.2314	0.0345

The impact of apodization parameter β on the Point Spread Function (PSF) intensity distribution is examined under various defocus and primary spherical aberration conditions.

Case 1: $\phi_d=\pi$ and $\phi_s=2\pi$

Increasing β from 0 to 0.5 decreases the central lobe's intensity. However, at β=0.75 and β=1, the intensity increases compared to β=0.5, but side lobes persist.

Case 2: $\phi_d=2\pi$ and $\phi_s=\pi$

Increasing β from 0 to 0.5 decreases the central lobe's intensity. At β=0.75, the intensity increases compared to β=0.5. Notably, at β=1, the intensity significantly increases compared to the unapodized case, and the first minima decrease compared to the Airy case.

Table 3. . Intensities and positions of maxima and minima of the PSF at defocus $\phi_d=2\pi$ and primary spherical aberration $\phi_s=2\pi$

		c. max		f. min		f. max	
	β	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
a=0.3, b=0.5, c=0.7 φd=2π, φs(r^4/4)=2π	**0**	0	0.094	2.0176	0.0713	3.4264	0.0806
	0.25	0	0.068	1.9043	0.0578	3.2598	0.0626
	0.5	0	0.0825	--	--	--	--
	0.75	0	0.1724	5.424	0.001	7.2785	0.0019
	1	**0**	**0.2568**	**3.9076**	**0**	4.8615	0.0012

Table 3 shows intensity distribution profiles for high defocus (ϕ_d=2π) and primary spherical aberration (ϕ_s=2π). For β=1, the first minima and side-lobes disappear, and the main peak's intensity significantly improves. The Point Spread Function (PSF) transforms into a super-resolved PSF with increased intensity and reduced central lobe width.

For β=0 (Airy case), high spherical aberration and defocus severely distort the principal maximum's intensity. The first maxima's intensity is high, but its axial shape and resolution are poor, with non-zero first minima.
As apodization increases from 0.5 to 1, lateral resolution consistently improves. For β=1, the central light flux exhibits high intensity compared to the Airy case, with zero intensity in the first minima, resulting in a super-resolved PSF.
With maximum apodization and ϕs=2π, intensity distributions for different defocus degrees show that for ϕd=2π, intensity equals the Airy case, and optical side-lobes are completely suppressed.

IV. Conclusions

This theoretical study explores the characteristics of aberrated optical systems under variable apodization, with a focus on enhancing the resolution of a four-zone optical system using various amplitude filters. The research examines the impact of Hanning, Triangular, Connes, and Polynomial filters on the optical system's performance in the presence of combined defocusing and primary spherical aberration. The study's findings reveal that variably apodized optical systems exhibit significant resolution improvement, particularly at higher degrees of apodization. Notably, higher orders of defocusing and primary spherical aberration enhance resolution, demonstrating the potential of variable apodization in mitigating the effects of aberrations. The four-zone pupil function is shown to improve resolution in terms of central lobe intensity, indicating that the optical system can effectively resolve composite images of two line objects with varying intensities. These results have significant implications for improving the performance of optical systems in various applications, including imaging, spectroscopy, and optical communication systems.

In conclusion, this research demonstrates the potential of variable apodization in enhancing the resolution of aberrated optical systems. The findings provide valuable insights for optimizing optical system design and improving image resolution in various fields. By tailoring the apodization parameters and amplitude filters, optical system designers can develop high-performance systems capable of producing high-resolution images and mitigating the effects of aberrations.

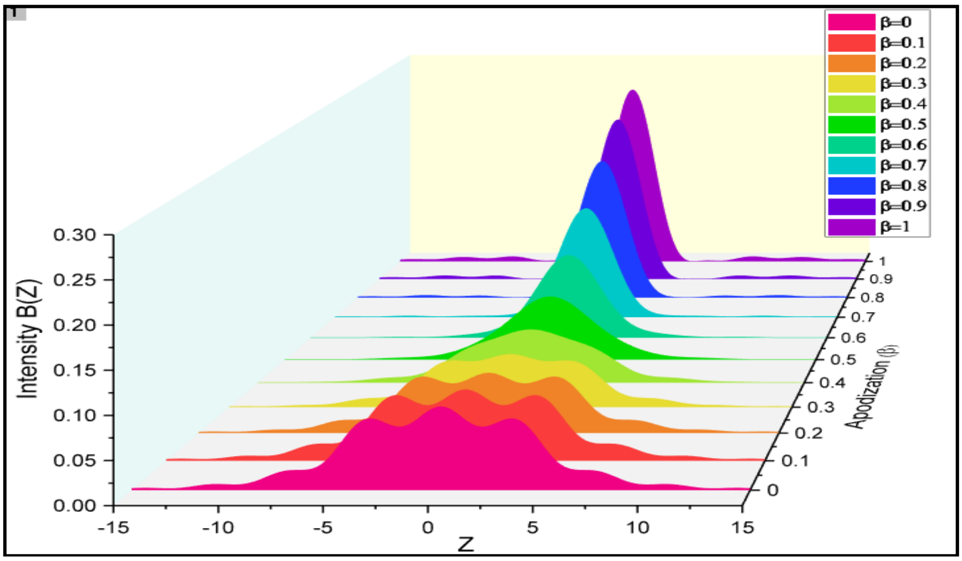

Figure3. 3D Waterfall Graph: Intensity Distribution of Four-Zone Amplitude PSF with defocus ϕ_d=2π and primary spherical aberration ϕ_s=2π

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