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Analyzing the Impact of Optical Factors on Telescope Image Quality

Effects of Aperture Shape, Aberrations, and Central Obstructions on the Point Spread Function

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ABSTRACT

Context. The image quality in telescopic observations is influenced by the Point Spread Function (PSF), which is affected by factors such as aperture shape, optical aberrations, defocusing, and central obstructions. Understanding these influences is critical for optimizing telescope design and improving image resolution in astronomical observations.
Aims. This study aims to examine the effects of different aperture shapes, defocusing, aberrations, and central obstructions on the PSF and the final image quality. By simulating various optical configurations, this work explores how each factor affects clarity and resolution for both point sources and extended sources, such as galaxies.
Methods. Using circular, square, and hexagonal apertures of different sizes, the PSF was generated by applying Fourier transforms to model the diffraction effects. Zernike polynomials were used to simulate defocusing and optical aberrations, including coma and spherical aberration. Additionally, central obstructions were introduced to the apertures to evaluate their impact on image clarity. The effects were assessed by convolving the PSFs with point and extended source models.
Results. The results show that each factor uniquely influences the PSF, with broader apertures yielding higher resolution, while aberrations and defocusing introduce blurring and asymmetry in the images. Central obstructions decreased central intensity. These outcomes highlight the need for precise optical design in telescopes.

Key words. telescope optics – point spread function – Zernike polynomials – image resolution – central obstruction

1. Introduction

Understanding the formation of images in telescopes and the factors that influence it is essential in astrophysics, where precise observations are crucial. Telescopes, whether refracting or reflecting, rely on optical elements like lenses and mirrors to focus light from distant sources into images. Each optical element has imperfections that can alter the way light is focused, introducing unique characteristics to the resulting image. These characteristics are defined by the Point Spread Function (PSF), which describes the system's response to a point source.

The **PSF** essentially represents the diffraction pattern observed at the focal point of the telescope when viewing a point source, such as a distant star. For ideal optical systems with a circular aperture and a flat wavefront, the PSF assumes the form of an **Airy pattern** due to Fraunhofer diffraction Hecht & Education (2017). The intensity distribution in the PSF corresponds to the square of the electric field intensity, allowing us to calculate the PSF by performing a Fourier transform on the telescope's aperture, translating the aperture's shape into the intensity distribution at the focal plane.

1.1. Aperture Shape and Diffraction

The PSF varies based on the aperture shape and size, affecting the resolution and clarity of images. Circular apertures produce radially symmetric diffraction patterns, but modern telescopes sometimes use segmented or non-circular apertures, such as square or hexagonal designs, to maximize light collection or fit specific design constraints. These shapes introduce different diffraction patterns that affect the clarity and resolution of images.

1.2. Image Formation through Convolution

For extended sources, such as galaxies, the image seen through a telescope is not a simple point but a collection of overlapping PSFs from each point on the source. Mathematically, this is represented as a **convolution** of the source's structure with the telescope's PSF. This convolution effectively blurs the image, with the degree of blurring dependent on the PSF's characteristics. Thus, the final image quality is directly related to the telescope's aperture design and the precision of its optical elements.

1.3. Wavefront Aberrations and Zernike Polynomials

Ideal optical systems assume a flat wavefront passing through the telescope's aperture, but atmospheric turbulence and imperfections in the optical elements can distort this wavefront. These deformations alter the phase of the incoming light wave, leading to various optical aberrations, such as **coma**, **astigmatism**, **spherical aberration**, and **defocus** Hecht & Education (2017).

Zernike polynomials are frequently used to model these aberrations, as they provide a series of orthogonal functions that represent different forms of wavefront distortion across a circular aperture. For example, defocusing is represented by a low-order Zernike polynomial, while higher-order polynomials can model complex aberrations like coma and spherical aberration. By applying Zernike polynomials to the aperture, we can simulate the effects of these aberrations on the PSF and examine how they degrade the final image.

1.4. Effects of Central Obstruction

Reflector telescopes typically have a secondary mirror at the center of the primary mirror, partially obstructing the aperture. This **central obstruction** modifies the PSF by reducing the central intensity and creating diffraction rings around the main peak. These rings can significantly affect the visibility of fine details, especially in extended sources, by reducing contrast and introducing artifacts into the image. Investigating the effects of different obstruction sizes helps to understand how design choices in telescope construction influence image quality.

This study explores these fundamental concepts by calculating the PSF for various aperture shapes, simulating defocus and aberrations using Zernike polynomials, and investigating the effect of central obstruction on image formation. Through this process, I aim to provide a comprehensive analysis of the factors that impact image quality in telescopes, helping to inform optical design choices that optimize resolution and clarity.

2. Methods

My analysis involved simulating the PSF for various aperture shapes, configurations, and optical effects in a telescope system. I applied a series of transformations to the aperture to observe their influence on the PSF and the resulting image of an extended and point source (a galaxy and a star). The steps included the following:

2.1. Aperture Generation for Circular, Square, and Hexagonal Shapes

I generated apertures of three different shapes: circular, square, and hexagonal. For each shape, I created apertures of varying sizes by specifying radii or side lengths. For circular apertures, I defined radii of 128, 64, and 32 pixels, while for square and hexagonal apertures, I used side lengths of the same values. The aperture masks were generated on a 2D grid of 256x256 pixels, and the corresponding PSF was computed by applying a 2D Fourier transform to each aperture. Each PSF was normalized for consistent intensity scaling, and the results were visualized and saved.

2.2. Simulation of Point Source and Extended Source (Star and Galaxy)

To simulate how the PSF affects different types of sources, I created two types of images: a point source (representing a star) and an extended Gaussian source (representing a galaxy). The point source was represented by a single bright pixel in the center of the grid, while the extended source was modeled as a Gaussian distribution with a standard deviation of 10 pixels. These source images allowed us to visualize how each aperture's PSF impacts both concentrated and spread-out light.

2.3. Defocusing Effect Using Zernike Polynomials

I simulated defocusing by introducing a phase shift in the circular aperture based on a Zernike polynomial. Specifically, I applied the defocusing Zernike polynomial $Z_2^0 = \sqrt{3}(2\rho^2 - 1)$ to introduce a radial phase shift, where ρ is the radial distance normalized to a maximum value of 1. The defocused PSF was computed and subsequently convolved with both the point source and the galaxy source, demonstrating how defocusing affects the final image.

2.4. Aberrations Using Zernike Polynomials

I applied additional Zernike polynomials to simulate common optical aberrations, including defocus, astigmatism (oblique and vertical), coma (vertical and horizontal), and spherical aberration. Each aberration type was represented by a specific Zernike polynomial, which was applied as a phase shift in the circular aperture. The resulting aberrated PSFs were visualized to observe the impact of each aberration on the telescope's optical performance.

A combined aberration effect was created by linearly combining spherical aberration and vertical coma using Zernike polynomials. Each aberration was assigned a weight (3.0 for spherical aberration and 1.5 for coma), and the resulting phase shift was applied to the circular aperture. The combined aberrated PSF was convolved with the galaxy source to observe the compounded impact of these two aberrations on the image quality.

2.5. Central Obstructions in the Aperture

Reflector telescopes often have a secondary mirror that partially obstructs the primary aperture. I simulated this effect by creating circular apertures with central obstructions of 0.1 and 0.5 times the primary mirror's radius. The PSFs for these obstructed apertures were calculated, and each was convolved with the galaxy source to examine the effects of different obstruction sizes on the image.

The code used in the analysis can be found in the following GitHub repository.

3. Results and Discussion

This section presents and interprets the outcomes of each stage in the analysis. The effects of various aperture shapes, configurations, and optical modifications on the PSF and galaxy image are examined in detail.

3.1. Circular, Square, and Hexagonal Aperture Shapes

In the first stage, I generated PSFs for circular, square, and hexagonal apertures with varying sizes (radii and side lengths of 128, 64, and 32 pixels). The results for the circular PSFs can be seen In Figure 1 while the others can be seen in the Appendix A. As expected, I observed that smaller apertures resulted in broader PSFs due to the increased diffraction effect, while larger apertures produced narrower, more concentrated PSFs. I couldn't observe the effects of the shape of the aperture due to the size of the grid. This baseline result highlights the role of aperture geometry in defining the telescope's resolution and PSF shape.

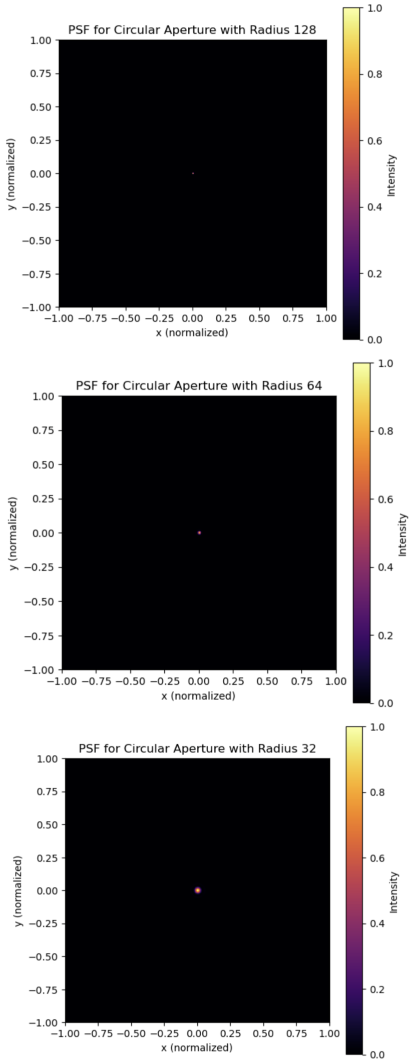

Fig. 1: Generated PSFs for circular apertures with varying sizes (radii of 128, 64, and 32 pixels).

3.2. Point Source and Extended Source (Galaxy) Simulation

To investigate the impact of PSFs on different types of sources, I used both a point source (star) and an extended Gaussian source (galaxy). When convolved with the PSFs from the circular aperture with 128 size, the point source images showed concentrated light. In contrast, the galaxy image convolved with the PSFs resulted in a more spread-out image. Both can be seen in Figure 2

3.3. Defocusing Effects

By applying a Zernike polynomial for defocus, I simulated the defocusing effect on the circular aperture seen in Figure 3. The defocused PSF was noticeably broader than the focused PSF, simulating the effect of image blurring due to defocus. When convolved with both the point source and galaxy source, the defocused PSF produced a noticeable blur in the images. The star (point source) retained some concentration of light but with reduced central intensity, while the galaxy (extended source) appeared more blurred.

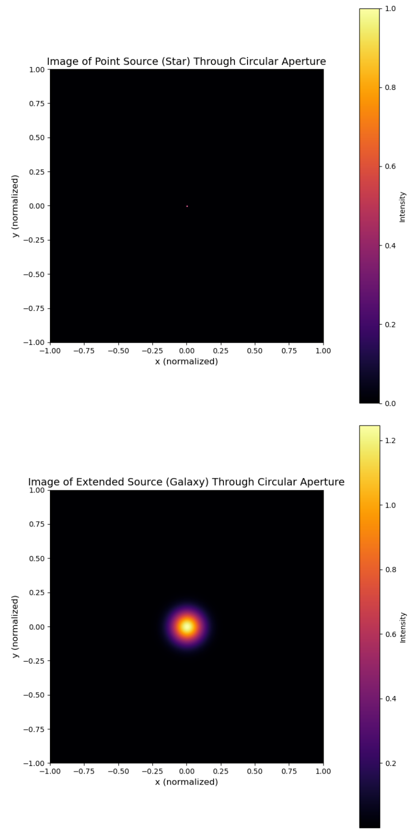

Fig. 2: PSF of circular aperture and 128 size on a point source and extended source.

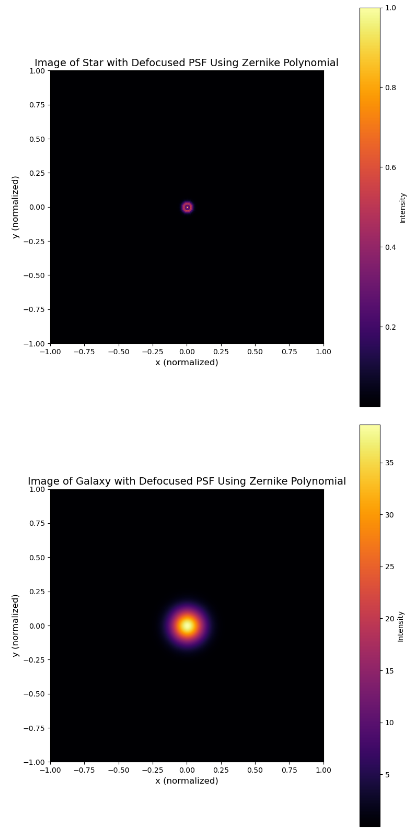

Fig. 3: The effect of defocuse on a point and extended source.

3.4. Optical Aberrations

I applied various Zernike polynomials to model specific aberrations, including astigmatism, coma, and spherical aberration. Each aberration had a distinct effect on the PSF and consequently on the resulting image Figure 4. Astigmatism introduced an elliptical distortion to the PSF, with both oblique and vertical forms producing different orientations in the elongation. Coma created an asymmetric "tail" effect in the PSF. Spherical aberration, in contrast, added a radially symmetric blur to the PSF, causing even light diffusion around the center. These aberrations illustrated how optical imperfections affect the PSF shape, leading to distortions and blurring that degrade image quality in specific ways.

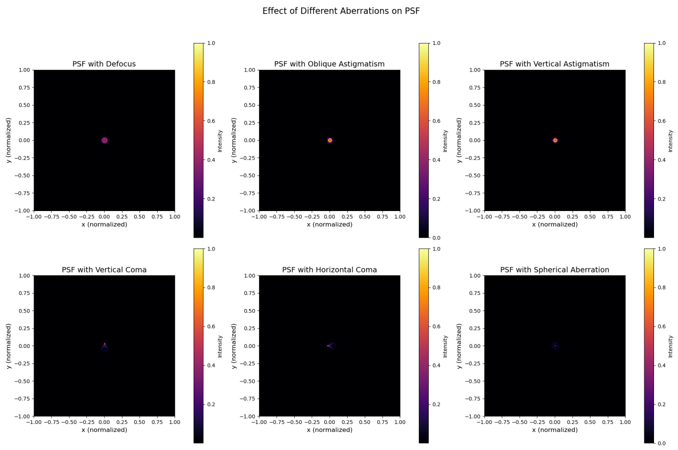

Fig. 4: The effect of defocuse on a point and extended source.

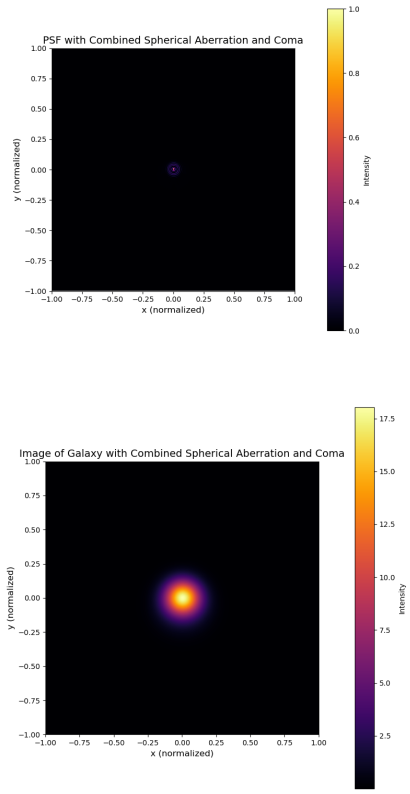

Fig. 5: The effect of the combination of spherical aberration and coma on a point source and an extended source.

3.5. Combined Spherical Aberration and Coma

To understand the impact of combined aberrations, I applied both spherical aberration and coma with different weights to create a PSF that reflected the combined effects Figure 5. The resulting PSF exhibited both the radial blur of spherical aberration and the asymmetric "tail" typical of coma. This outcome demonstrates how multiple aberrations can interact to produce complex PSF shapes that can significantly distort images.

3.6. Central Obstructions

Finally, I examined the effects of central obstructions, simulating the impact of secondary mirrors in reflector telescopes. I generated apertures with central obstructions of 0.1 and 0.5 times the primary mirror's radius Figure 6. In the resulting PSFs the central intensity was reduced in both cases.

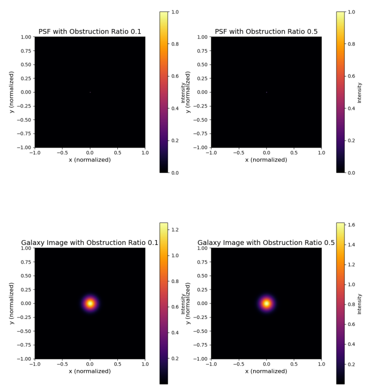

Fig. 6: The effect of obstruction on a point source and an extended source.

4. Conclusion

This study explored how various factors influence the Point Spread Function (PSF) and image quality in telescopic systems. By examining the effects of aperture shape, defocusing, wavefront aberrations, and central obstructions, I gained insights into the unique ways each aspect contributes to image clarity and distortion.

I found that aperture shape has a significant impact on the PSF, with circular apertures yielding symmetric diffraction patterns, while square and hexagonal apertures introduced distinct geometric features. Defocusing and wavefront aberrations—simulated using Zernike polynomials—demonstrated how imperfections in optical elements can introduce blurring, asymmetry, and radial distortions to the PSF, each affecting image clarity differently. The combined effects of spherical aberration and coma highlighted how multiple aberrations can compound, resulting in complex distortions in the final image, particularly for extended sources like galaxies.

Finally, I investigated the effect of central obstructions, typical in reflector telescopes with secondary mirrors, and observed that these obstructions reduce central intensity and introduce ring-like diffraction artifacts, impacting image contrast and detail visibility.

In summary, this analysis provides a comprehensive overview of the optical effects that influence image quality in telescopes. These findings emphasize the importance of carefully managing design choices, such as aperture geometry and obstruction minimization, to enhance resolution and image fidelity. Through this work, I hope to contribute to the understanding of optical factors in telescope design, supporting efforts to optimize instruments for high-precision astronomical observations.

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Appendix A: Square and Hexagonal Aperture Shapes

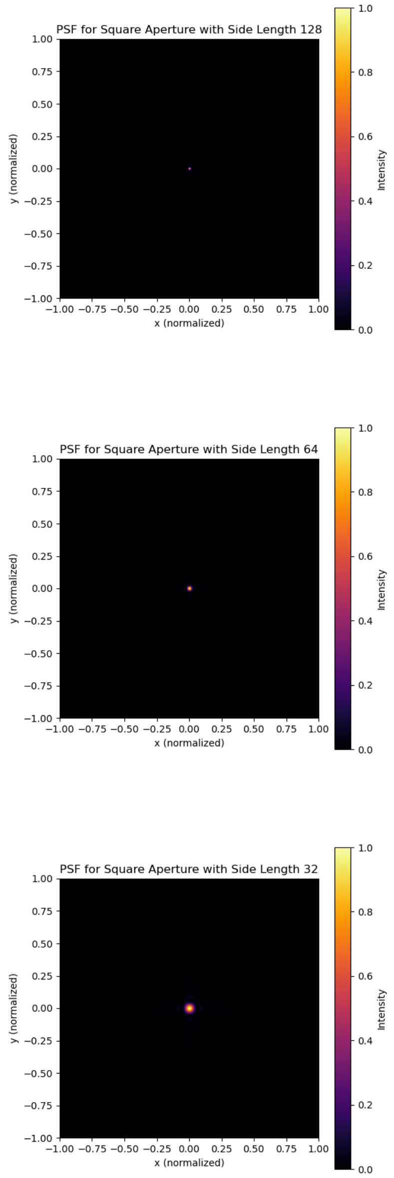

Fig. A.1: Generated PSFs for square apertures with varying sizes (side lengths of 128, 64, and 32 pixels).

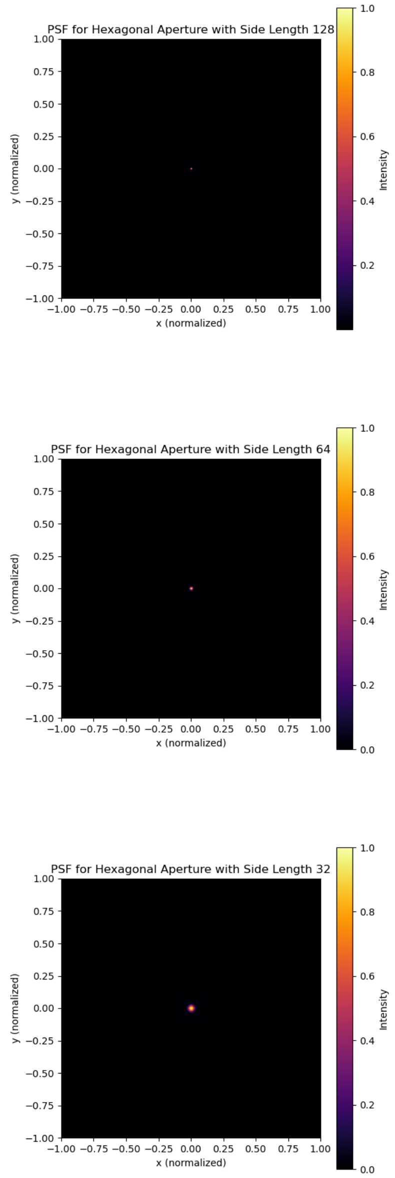

Fig. A.2: Generated PSFs for hexagonal apertures with varying sizes (side lengths of 128, 64, and 32 pixels).

References

Hecht, E. & Education, P. 2017, Optics, 5th edn. (Pearson, Cop)