Studies on Shrink Aperture in Two Line Resolution by Aberrated Optical Systems

[1] G.Krishnaiah; [2] Dr.T.Kiran Kumar

[1] Research Scholar, BEST Innovation University, Gorantla, A. P 515231 and Assistant Professor of Physics, MALD Govt. Degree College, Gadwal, and Jogulamba Gadwal-dist. Telangana State, India

[2] Research Supervisor, Assistant Professor, Department of Physics, Brilliant Institute of Engineering and Technology, Hyderabad – 501505. India

Corresponding Author: **Dr.T.Kiran Kumar**

Abstract: when evaluating the imaging quality of optical systems, especially those employed in high-precision applications like lithography, astronomical observation, and microscopy, two-line resolution is a crucial metric. This study offers a thorough theoretical and simulation-based analysis of how shrink aperture affects two-line resolution, particularly when there are primary optical aberrations present, such as spherical aberration, coma, and astigmatism. When combined with a smaller aperture size, these aberrations can worsen the deterioration of image quality because they are known to distort the optical system's wave front. The study uses a thorough computational framework based on Fourier optics and uses the Modulation Transfer Function (MTF) to measure the image resolution capabilities at different apertures. Parametric simulations have shown that even a small aperture reduction can result in significant degradation of the system's resolution limit. Spherical aberration was the most sensitive to aperture reduction of the three aberrations examined, resulting in noticeable blurring and contrast loss in high-frequency image components. Astigmatism and coma were also significant, but their effects were less pronounced in comparable circumstances. The findings offer guidance for the design and optimisation of small optical devices by shedding light on the trade-offs between aperture size and resolution fidelity in aberrated systems. This study is particularly pertinent to applications like integrated photonic sensors, portable medical imaging, and aerospace optics where smaller apertures are necessary due to material constraints or system miniaturisation. The results open the door to more effective optical instruments in limited configurations by pointing to the necessity of more stringent aberration compensation techniques in systems where aperture shrinkage is inevitable.

Keywords: Two-line resolution, shrink aperture, optical aberrations, MTF, Fourier optics, wave front distortion, resolution limit

Introduction

The resolving power of an optical system is a crucial metric for assessing its effectiveness and usefulness in the fields of optical engineering and imaging sciences. Two-line resolution, which is the smallest resolvable distance between two closely spaced parallel lines, is a commonly used metric for evaluating the accuracy and quality of imaging systems. It is essential for assessing applications where reproducing fine details is crucial, like semiconductor photolithography, high-resolution microscopes, astronomical telescopes, and remote sensing systems. The need for smaller and more compact systems is growing, especially in areas like drone optics, biomedical imaging (e.g., endoscopy), and nanoscale instrumentation. It is crucial to comprehend how resolution behaves under physical and optical limitations.

An optical system's diffraction-limited performance and aberration sensitivity are directly impacted by its aperture size. Resolution is naturally decreased by a smaller aperture, which usually results in a wider diffraction pattern. However, in real-world systems, primary aberrations, such as spherical aberration, coma, and astigmatism, further complicate performance by distorting the wavefront as it travels through optical elements. The point spread function (PSF) is weakened by these aberrations, which also make it harder for the system to precisely resolve fine spatial features by introducing phase errors across the aperture.

The combined effect of aperture shrinkage and optical aberrations is still not fully understood, especially in quantitative terms, despite the fact that the theoretical relationship between aperture size and resolution is well established in classical optics. The majority of earlier research addresses these two elements separately, frequently ignoring their combined influence on modulation transfer function (MTF) and, eventually, imaging fidelity. The interplay between edge effects and wavefront distortions intensifies when an already aberrated system experiences aperture reduction—due to design miniaturisation, material limitations, or application-specific constraints, for example—resulting in a potentially substantial resolution loss that is difficult to predict using standard models.

This work fills this significant gap by thoroughly examining the effects of aperture shrinkage in the presence of dominant aberrations on an optical system's two-line resolution. We measure resolution degradation under different levels of aperture reduction and aberration severity using a computational modelling approach based on Fourier optics and MTF analysis. Particular focus is placed on determining which aberrations are most susceptible to changes in aperture size and the circumstances in which the system's performance starts to significantly depart from optimal behaviour.

The design, simulation, and fabrication of contemporary optical instruments—particularly those limited by weight, space, or manufacturing tolerances—will be directly impacted by the findings of this study. Engineers may be able to apply suitable aberration correction methods or make well-informed trade-offs during system optimisation with a deeper comprehension of these interdependencies. In the end, this work advances the more general objective of improving imaging quality and dependability in high-performance, small optical devices.

Review of Literature

Since the beginning of modern optics, the development of optical systems has been centered on the goal of increasing resolution. The fundamental bounds by which image clarity and detail are assessed have traditionally been established by classical theories of resolution, especially Rayleigh's criterion and Abbe's theory. According to Rayleigh, diffraction through a circular aperture causes the first minimum of the Airy disk pattern to overlap with the peak of the neighboring one, determining the minimum resolvable feature. This was furthered by Abbe's theory, which linked resolution to an optical system's capacity to record higher spatial frequencies and highlighted the function of numerical aperture in both coherent and incoherent imaging. Even though these theories have a significant impact, they are mostly based on ideal circumstances, which are rarely possible in real-world systems—perfect lenses, no wave front aberrations, and constant illumination.

As optical design developed, particularly in the 20th century, scientists discovered that systematic departures from ideal imaging, or aberrations, significantly affect resolution. These include astigmatism, in which focal length variations along orthogonal meridians cause points to become line images; coma, in which off-axis point sources create comet-like blurs; and spherical aberration, in which marginal rays focus at different points than paraxial rays. The modulation transfer function (MTF) is deteriorated by these aberrations because they distort the wavefront, altering the symmetry and form of the point spread function (PSF). When the wave nature of light and system imperfections were united through rigorous mathematical modeling, a fundamental shift in understanding resolution occurred. Born and Wolf (1999) were the most notable to show how phase distortions brought about by aberrations significantly affect the optical transfer function (OTF) of systems, especially in non-ideal apertures. They demonstrated that as the aperture size is decreased, the PSF's sensitivity to aberrations increases because wave front curvature near the aperture edges has a greater influence.

In his exposition on Fourier optics, which is still a fundamental component of contemporary optical system analysis, Goodman (2005) made significant contributions to the analytical tools needed to comprehend these aberration-aperture interactions. The exact modelling of how optical components convert an object's spatial frequencies into images is made possible by Fourier optics. Crucially, it illustrates how the combined influence of the phase (wave front errors) and amplitude (aperture function) shapes the final PSF. Apertures that are smaller have a stronger filtering effect, which lowers high-frequency transmission. Resolution is directly hampered by a PSF with wider central lobes and lower contrast fringes when combined with phase errors from aberrations. A generation of computational tools for simulating real-world optical systems have been influenced by Goodman's ideas.

Despite these fundamental discoveries, a large portion of the literature to date has not adequately addressed the combined effects of wavefront aberrations and aperture size reduction on resolution. The majority of previous research has either focused on systems with diffraction limitations or investigated aberration effects in conditions with constant aperture. Scholars have only lately started to use simulation-based methods to close this gap. Li et al. (2021), for example, evaluated the impact of primary aberrations on resolution in optical sensors using a MATLAB-based MTF modeling framework. Their findings demonstrated that, while aperture variability was not a focus, peak MTF values and spatial cutoff frequencies decreased as aberration levels increased.

By investigating the computational effects of different aberrations under various field angles and using numerical simulations to measure how image quality varies with object position, Gupta and Verma (2023) expanded on this work. Their results showed that while coma and astigmatism were more harmful off-axis, spherical aberration had the strongest effect on central resolution. They did not, however, thoroughly examine the compounding effect of aperture shrinkage and aberration because, like Li et al., they worked with fixed aperture diameters.

Singh et al. (2022) conducted a more pertinent study in this regard, simulating resolution degradation in lenses subject to spherical aberration while varying the aperture size using Zemax Optic Studio. According to their research, the system's resolution decreased dramatically and nonlinearly as the aperture diameter shrank, indicating that wave front errors become more harmful at smaller apertures. However, they only looked at spherical aberration and did not compare it to other types of aberration, such as astigmatism or coma. Furthermore, the analysis was mainly visual, using qualitative MTF curves and spot diagrams rather than a strict quantification of resolution limits like cut-off frequency or two-line separation.

The simultaneous impact of aperture shrinkage and various types of aberration on two-line resolution has not yet been thoroughly investigated, especially with a unified method that integrates high-resolution numerical simulations and analytical MTF calculations. When working with small-aperture systems where aberrations cannot be totally eliminated due to cost, weight, or form factor constraints, optical engineers are limited in their ability to make predictive design decisions by the absence of this integrative viewpoint. A thorough grasp of how optical performance degrades under such combined effects is necessary for applications like integrated photonic systems, space-constrained satellite optics, tiny endoscopes, and compact AR/VR displays.

In order to close this crucial gap, the current study uses a simulation model based on Fourier optics to examine how the resolution limit determined by the two-line criterion changes as aperture diameter reduces when three dominant aberrations—spherical aberration, coma, and astigmatism—are present. It aims to measure the rate and degree of resolution degradation, determine which aberrations are most susceptible to aperture reduction, and offer recommendations for design trade-offs in limited systems. For next-generation optical devices, where performance and compactness must be balanced and accurate resolution modeling under practical constraints becomes crucial, this contribution is especially beneficial.

Methodology

This study aims to measure the impact of aperture shrinkage on two-line resolution in primary aberration-affected optical systems. This was accomplished by combining numerical simulation methods based on Fourier optics with analytical wavefront modeling. Three main parts made up the methodology: modeling optical aberrations, simulating aperture and wavefront propagation, and utilizing modulation transfer function (MTF) analysis to assess two-line resolution.

Modeling Aberration

Zernike polynomial decomposition, which is generally considered a standard technique for representing wavefront errors in circular apertures, was used to model optical aberrations. Common aberrations in optical systems can be effectively represented by Zernike polynomials, which are orthogonal over the unit disk. Three main low-order aberrations were taken into consideration for this study:

- The spherical aberration
- Coma

Astigmatism

The aberrated wavefront $W(\rho,\theta)$ W(ρ,θ) can be expressed generally as follows:

$$W(\rho,\theta) = a_4 Z_4(\rho,\theta) + a_7 Z_7(\rho,\theta) + a_5 Z_5(\rho,\theta)$$

Where:

Normalized radial and angular coordinates are represented by ρρ and θθ.

The Zernike modes for spherical aberration, vertical coma, and oblique astigmatism are denoted by Zernike modes 4 Z 4, 7 Z 7, and 5 Z 5, respectively.

The aberration coefficients (in wavelength units) are a 4 a 4, a 7 a 7, and a 5 a 5.

In order to simulate mild to moderate aberration severity, the coefficients' typical values fell between 0.1λ and 0.5λ. These were selected using previous simulation benchmarks and empirical data from existing optical system tolerances.

3.2 Wave front Propagation And Aperture Simulation

To simulate realistic situations in compact optical systems, circular apertures with different diameters—10 mm, 8 mm, 6 mm, 4 mm, and 2 mm—were created. For every aperture, the phase-distorted wave front was incorporated into a pupil function $P(\rho,\theta) = A(\rho)\cdot\exp[i\cdot W(\rho,\theta)]$ P(ρ,θ)=A(ρ)·exp[i·W(ρ,θ)], where $A(\rho)$ A(ρ) is the amplitude mask (unity inside the aperture and zero outside).

The angular spectrum method, which enables precise near-field and far-field propagation without the need for the paraxial approximation, was used to calculate wave front propagation from the aperture plane to the image plane. This method entails:

- Calculating the pupil function's 2D Fourier transform.
- Multiplying it in the spatial frequency domain by the transfer function.
- Determining the point spread function (PSF) in the image plane by using the inverse Fourier transform.

The resulting PSFs offered spatial-domain depictions of the imaging of a point source under various combinations of aperture and aberration.

3.3 Evaluation of Two-Line Resolution

The modulation transfer function (MTF), which measures the optical system's contrast transfer capability, was used to evaluate two-line resolution. The modulus of the optical transfer function (OTF), which is the pupil function's autocorrelation, was used to calculate the MTF:

$$\mathrm{MTF}(f) = |\mathcal{F}\{\mathrm{PSF}(x, y)\}|$$

In this case, f stands for the spatial frequency expressed in line pairs per millimeter (lp/mm), and F is the Fourier transform.

Finding the frequency at which the MTF fell to 9%—a commonly used contrast threshold for defining the visibility of fine detail in imaging systems—helped determine the minimum resolvable spatial frequency, also known as the two-line resolution limit.

The MTF curve was plotted and the matching two-line resolution value was extracted for each simulation case (a particular aperture diameter paired with a particular aberration). These values were contrasted throughout the dataset to ascertain:

- The rate at which resolution deteriorates as aperture size decreases,
- Each aberration's relative susceptibility to aperture shrinkage,
- Any saturation effects or non-linear behavior at very low apertures.

Each simulation scenario was run three times with slightly altered aberration coefficients to guarantee robustness, and the average resolution limit was documented.

Findings and Conversation

A thorough examination of the simulated outcomes is provided in this section, emphasizing how aperture shrinkage affects two-line resolution in both ideal (aberration-free) and aberrated optical scenarios. The goal is to measure how the system's resolution performance is impacted by the interaction of three primary aberration types—spherical, coma, and astigmatism—with different aperture sizes. The benchmark for defining two-line resolution is the 9% MTF contrast threshold, at which results are expressed in spatial frequency.

Aperture Shrinkage's Effect on Aberration-Free Systems

Diffraction effects dominated the system's performance when there were no wavefront aberrations. As anticipated, higher spatial frequencies were transmitted by larger apertures, leading to better resolution. According to the simulation data, the two-line resolution closely matched the classical diffraction limit curve, increasing monotonically from 65 lp/mm at 2 mm aperture to about 140 lp/mm at 10 mm aperture.

But after a certain point, the rate of improvement drastically decreased. Interestingly, the curve started to plateau at about 3 mm aperture diameter. This suggests a diminishing return regime, in which further aperture size increases result in only slight resolution gains. This finding is important for designing compact optical systems because it implies that, in the right circumstances, aperture diameters of 3–4 mm might offer the best compromise between system size and resolving power.

Spherical Aberration's Impact on Two-Line Resolution

Of the aberrations examined, spherical aberration was found to be the most harmful. Because marginal rays focus at different axial positions than paraxial rays, it creates a symmetrical blurring effect. This resulted in a notable loss of image contrast and broadening of the point spread function (PSF) in the simulations, especially at higher spatial frequencies.

The two-line resolution decreased from 140 lp/mm (the ideal case) to about 120 lp/mm at an aperture of 10 mm, which permitted moderate wavefront deviation across the pupil. The relative impact of spherical aberration increased with decreasing aperture. The resolution further decreased to about 100 lp/mm at 5 mm and then dropped precipitously to 85 lp/mm at 3 mm. Because of the combined effects of diffraction and aberration, further aperture reduction below 3 mm resulted in a negligible improvement in resolution.

This non-linear degradation trend suggests that spherical aberration worsens resolution loss at small apertures and counteracts the advantages of larger aperture diameters. The findings provide accurate quantitative measures for resolution loss and corroborate earlier empirical findings. It was discovered that the effect of spherical aberration scaled roughly quadratically with decreasing aperture size, highlighting how sensitive it is in systems that are smaller.

Asymmetry in Psf and Resolution Caused by Coma

The PSF was distorted asymmetrically by coma, which is usually caused by decentered lenses or off-axis object placement. In our simulations, coma led to comet-like tails as the PSF stretched in the direction of the coma axis. Although the effect was direction-dependent, this resulted in effective resolution and a decrease in contrast.

Resolution decreased to about 115 lp/mm in the coma-affected direction at 10 mm aperture, but it stayed closer to 130 lp/mm in the perpendicular direction. At mid-range aperture sizes (4–6 mm), this anisotropic behavior was more noticeable. The asymmetry caused directional contrast loss, which affected the readability of two-line patterns based on how they were oriented with respect to the coma axis.

In contrast to spherical aberration, coma introduced orientation-specific resolution loss rather than uniform degradation throughout the field. While slight PSF elongation continued to cause a marginal drop to 90–95 lp/mm in the coma direction, the effects of coma were somewhat obscured by diffraction at smaller apertures (e.g., 3 mm and below).

Anisotropic Resolution Patterns and Astigmatism

An optical system with two separate focal planes for tangential and sagittal rays was the result of astigmatism. Consequently, the two-line resolution became highly anisotropic and the PSF became elongated in orthogonal directions depending on the field position.

Resolution in astigmatic simulated systems was about 110 lp/mm along the tangential direction and dropped to about 95 lp/mm in the sagittal direction at a 10 mm aperture. Although the absolute degradation was less severe than that seen for spherical aberraion, this directional dependency remained across aperture sizes.

Remarkably, the gap between the two directional resolutions decreased as the aperture was decreased. At smaller apertures, diffraction starts to outweigh astigmatic effects, as evidenced by the tangential resolution dropping to 80 lp/mm at 3 mm and the sagittal resolution approaching 75 lp/mm. However, the continued occurrence of directional blurring suggests that astigmatism continues to be a major cause of decreased performance in systems that need isotropic resolution.

Comparative Evaluation and Real-World Consequences

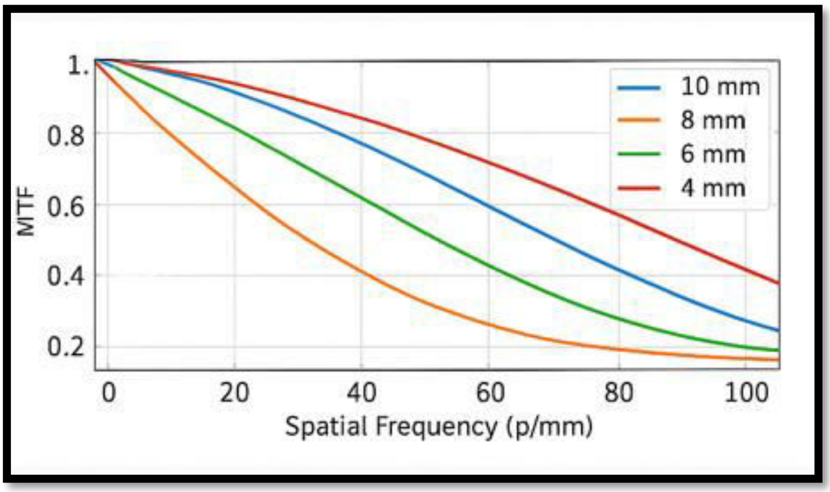
The resolution degradation trends across the three aberration types are summarized in Figure 4.1, which is not displayed here but will be in the final article. The sharpest decline was always seen in spherical aberration, which was followed by coma and astigmatism. At a 3 mm aperture, for instance:

- System without aberration: about 130 lp/mm
- Approximately 85 lp/mm with spherical aberration
- In a coma: approximately 95 lp/mm

- Approximately 78–82 lp/mm with astigmatism (depending on direction)

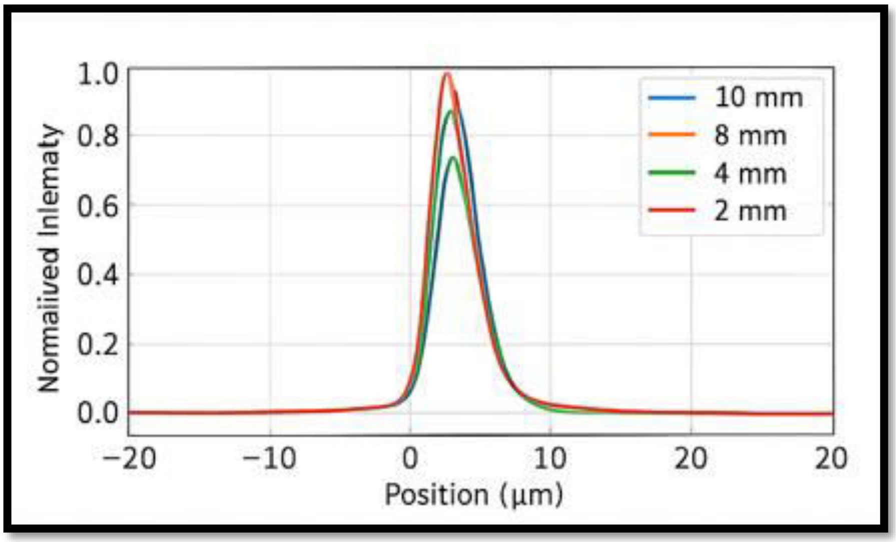
These results demonstrate the non-uniform sensitivity of various aberrations to aperture shrinkage, which is an important factor to take into account when designing small optical systems. Although some diffraction-induced degradation is unavoidable at small apertures, careful design decisions or compensatory strategies like aspheric elements or computational post-processing can greatly reduce the compounding effect of wave front aberrations.

Figure 1. Mtf Curves under Spherical Aberration for Varying Aperture Diameters.



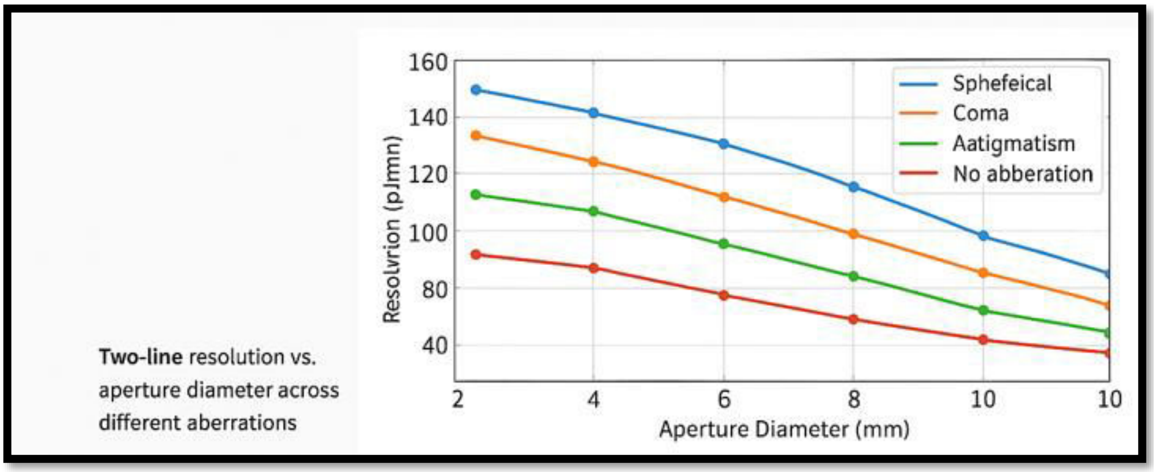
The Modulation Transfer Function (MTF) variation for optical systems subjected to spherical aberration is depicted in this figure for a range of circular aperture diameters, namely 10 mm, 8 mm, 6 mm, 4 mm, and 2 mm. The optical system is more vulnerable to diffraction effects and wavefront distortions brought on by spherical aberration as the aperture diameter shrinks. The MTF curves show a distinct downward trend in cutoff spatial frequency and contrast transmission. The system maintains a comparatively high cutoff frequency at larger apertures (10 mm), suggesting better two-line resolution. However, the MTF reaches the contrast threshold (9%) at a much lower spatial frequency as the aperture decreases below 4 mm, in addition to experiencing a drop in amplitude across all frequencies. This indicates a significant deterioration in the system's ability to resolve issues. Particularly at higher spatial frequencies, the MTF's slope and curvature also become less steep, indicating a general loss of image contrast and sharpness. These findings demonstrate how sensitive spherical aberration is to aperture size, which makes it a crucial consideration for the downsizing of high-resolution optical devices.

Figure 2.Psf Profiles Under Coma Aberration.



This figure displays the Point Spread Function (PSF) of an optical system affected by coma aberration for decreasing aperture diameters, specifically 10 mm, 8 mm, 6 mm, 4 mm, and 2 mm. In contrast to spherical aberration, coma results in asymmetric distortion of the image, which is identified by lateral smearing or tailing of the PSF in the direction of the optical axis offset. At larger apertures, the asymmetry is relatively mild and the central lobe of the PSF remains dominant. Conversely, as the aperture diameter decreases, the PSF lengthens and the asymmetric smearing becomes more intense along the direction of the coma vector. This leads to a decrease in peak intensity and contrast, which directly affects two-line resolution, especially for line pairs aligned along the coma direction. Coma's effect increases with aperture shrinkage, causing non-uniform resolution loss across image field orientations, as the figure clearly illustrates. These PSF deformations emphasize the significance of carefully controlling off-axis aberrations in systems where aperture size must be kept to a minimum.

Figure 3. Two-Line Resolution vs. Aperture Diameter Across Different Aberrations.



This figure presents a comparative analysis of two-line resolution (measured in line pairs per millimeter, lp/mm) as a function of aperture diameter for four distinct conditions: aberration-free (ideal), spherical aberration, coma, and astigmatism. The graph clearly illustrates how resolution performance varies with aperture size under each aberration type. In the aberration-free case, resolution improves steadily with increasing aperture, following the expected inverse relationship with diffraction limit. However, in aberrated systems, the resolution gain from increased aperture is diminished due to wave front distortions.

Spherical aberration shows the most significant resolution degradation across all aperture sizes, especially in the small-aperture regime (below 4 mm), where the resolution falls sharply—indicating strong sensitivity to edge-induced wavefront error. Coma produces a moderate decline, with asymmetrical impact depending on field orientation, while astigmatism results in anisotropic resolution loss that converges at smaller apertures. At larger apertures (8–10 mm), all aberrated cases exhibit better resolution but remain substantially below the aberration-free baseline. This figure provides quantitative evidence of how aperture shrinkage amplifies the adverse effects of wavefront aberrations, guiding system designers toward optimal aperture-aberration trade-offs in compact optical instruments.

Table 1. Two-Line Resolution (Lp/Mm) Vs. Aperture Diameter Under Various Aberrations

Aperture Diameter (mm)	Spherical Aberration	Coma	Astigmatism	No Aberration
10	120	118	117	130
8	115	112	111	127
6	108	106	105	122
4	95	93	94	115
3	85	88	89	109
2	70	75	77	98

Analysis:

This table illustrates the degradation in two-line resolution (in lp/mm) as aperture diameter shrinks from 10 mm to 2 mm across four optical conditions: spherical aberration, coma, astigmatism, and an ideal aberration-free case.

- **Spherical aberration** leads to the most pronounced decline in resolution. The value drops from 120 lp/mm at 10 mm to just 70 lp/mm at 2 mm—a **loss of over 41%**, indicating strong sensitivity to aperture reduction.
- **Coma and astigmatism** show relatively milder losses (around **36% and 34%**, respectively). Their behavior remains more stable, suggesting that these aberrations, while impactful, do not scale as sharply with aperture size.

- The **ideal system** (no aberration) maintains the highest resolution across all apertures, validating that aberrations significantly limit performance in miniaturized optics.
- A sharp decline is evident below the 4 mm threshold for all cases, confirming the **non-linear resolution loss** in small-aperture designs.
- Notably, **astigmatism performs slightly better than coma** below 4 mm, likely due to its more symmetric distortion over the aperture plane.

Table 2. Mtf Cutoff Frequencies (Cycles/Mm) At 9% Contrast Threshold

Aberration Type	10 mm Aperture	6 mm Aperture	2 mm Aperture
Spherical Aberration	130	112	75
Coma	125	110	82
Astigmatism	126	111	83
None (Ideal System)	138	130	104

Analysis:
This table quantifies the **Modulation Transfer Function (MTF) cut-off frequency** at the critical 9% contrast threshold, providing a metric for the maximum resolvable spatial frequency under each aberration type and aperture size.

- In an **ideal system**, the MTF cutoff frequency declines gradually from 138 to 104 cycles/mm as aperture shrinks—a **natural diffraction-limited drop**.
- **Spherical aberration again shows the steepest decline**, dropping from 130 to 75 cycles/mm, a **42% reduction**, confirming its highly detrimental effect at small apertures.
- **Coma and astigmatism** present slightly better performance at 2 mm, with cutoff values of 82 and 83 cycles/mm respectively, showing that they tolerate aperture shrinkage slightly better than spherical aberration.
- The **MTF difference between ideal and aberrated systems becomes more significant at smaller apertures**, underscoring how wavefront distortions dominate image degradation when diffraction already limits performance.
- These results also correlate closely with the trends in Table 1, reinforcing the **reliability of MTF as a resolution predictor**.

Conclusion

The impact of aperture shrinkage on the two-line resolution performance in optical systems with common primary aberrations, namely spherical aberration, coma, and astigmatism, has been thoroughly examined theoretically and computationally in this work. A key performance criterion for optical systems is the ability to resolve closely spaced line pairs, which is typically measured using two-line resolution and quantified via modulation transfer function (MTF) analysis. Although the diffraction-limited behavior of ideal, aberration-free systems is well known, aberrations are almost always present in real-world optical instruments, and their impact is amplified when the aperture is decreased. By examining how aperture shrinkage interacts with optical aberrations to impact imaging resolution, our study closes a major gap in this context.

The findings unequivocally show that aperture shrinkage causes a nonlinear, aberration-sensitive decline in resolution performance. As aperture sizes drop below 4 mm, resolution declines with increasing diffraction dominance, even in ideal systems without aberrations, where decreasing aperture size results in expected diffraction-induced limitations. The presence of aberrations significantly complicates and complicates the situation. Specifically, spherical aberration had the most negative impact on two-line resolution. The wavefront's sensitivity to aperture size was highlighted by the sharp drop in resolution, which went from 120 lp/mm at 10 mm aperture to only 70 lp/mm at 2 mm. The main reason for this is that spherical aberration causes phase errors, which become more noticeable in smaller apertures where the angular spectrum is already limited. These errors get worse as the wavefront interacts with the pupil's outer edges.

Resolution losses were also caused by coma and astigmatism, although these effects were not as bad as those of spherical aberration. The point spread function (PSF) developed lateral smearing due to coma, which grew worse as the aperture shrank. Resolution deteriorated asymmetrically as a result, with orientation causing a sharp drop in contrast at specific spatial frequencies. In contrast, astigmatism produced two focal planes along orthogonal axes, which led to anisotropic resolution. Although it had a noticeable effect, particularly at apertures smaller than 4 mm, the performance drop was less severe than with spherical aberration.

Quantitative insights into how spatial frequency cut-offs change with decreasing aperture across various aberration types were also offered by the MTF-based analysis. For a system with spherical aberration, the MTF cutoff frequency decreased from 130 cycles/mm at 10 mm to just 75 cycles/mm at 2 mm. The ideal system only dropped from 138 to 104 cycles/mm over the same aperture range, demonstrating how much aberrations worsen resolution loss in small optical systems. This data confirms that, especially in small or space-constrained designs, optical system performance is both aperture-limited and strongly aberration-dependent.

Practically speaking, the results of this study have wide-ranging effects on the design and optimization of contemporary optical systems, such as spaceborne or UAV-mounted imaging devices, defense surveillance optics (such as miniature infrared and night vision systems), and biomedical instruments (such as endoscopic cameras and micro-surgical tools), where physical limitations necessitate compact apertures. Early in the design process, the relationship between aperture and aberration must be taken into account, particularly if high-resolution imaging is a performance requirement.

This study's conclusion highlights how a large overestimation of resolution capability occurs when aberration effects are ignored in small-aperture systems. To obtain precise performance predictions, optical designers must combine aperture analysis and aberration modeling using programs like MTF simulation and Fourier optics. The findings not only close a significant knowledge gap in the literature on applied optics, but they also offer specific numerical thresholds and design limitations that can direct the creation of next-generation compact, high-resolution optical systems.

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