Introduction to Adaptative Optics

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Abstract

A flat wavefront was distorted using a spatial light modulator to simulate atmospheric aberrations. These distortions were measured with a Shack-Hartmann sensor and corrected using a deformable mirror. Manual and feedback compensation methods were tested, showing effective correction for concave aberrations, while convex aberrations proved more challenging. The experiment demonstrated the fundamentals of adaptive optics and its limitations.

1 Introduction

Adaptive optics (AO) is a technique developed to compensate for wavefront distortions introduced by atmospheric turbulence or optical system imperfections. These distortions degrade the quality of optical imaging by altering the phase front of incoming light, resulting in blurred or deformed images. The wavefront is an imaginary surface connecting points of equal phase in a propagating beam. Any deformation of this surface leads to optical aberrations. By accurately characterizing these deviations, adaptive systems can employ deformable mirrors to counteract them, restoring the wavefront.

To describe such distortions mathematically, the aberration function $\phi(\rho, \theta)$ is commonly expanded in terms of Zernike polynomials (Z_i). These are a set of orthogonal functions defined over a unit circle, each corresponding to a specific type of optical aberration.

$$\phi(\rho, \theta) = \sum_{i}^{\infty} a_i Z_i(r, \theta) \tag{1}$$

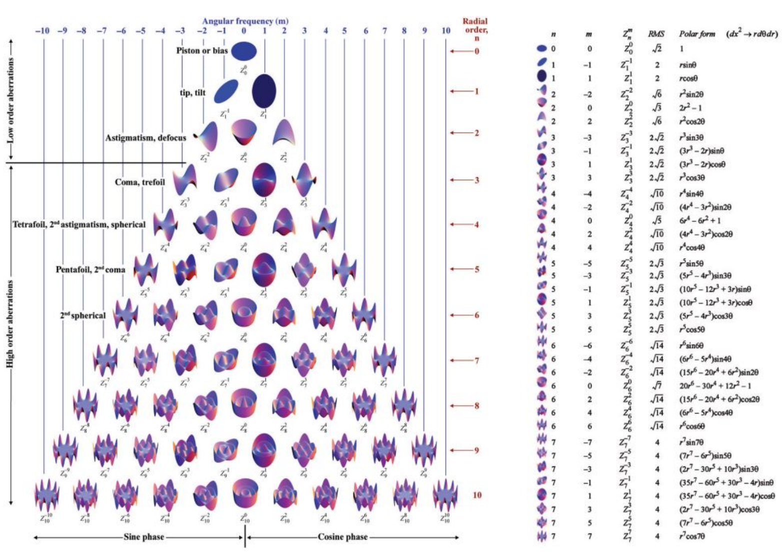

Figure 1: On the left, hierarchical arrangement of Zernike modes according to radial order n and azimuthal frequency m, illustrating the structure of common wavefront aberrations. On the right, mathematical expressions of the lower-order Zernike polynomials in polar coordinates, each corresponding to a classical aberration such as tilt, defocus, or astigmatism [7].

While a perfect correction would require an infinite number of terms, practical implementations focus on the dominant low-order components.

To evaluate the degree and nature of the aberration, there are some parameters such as the Strehl ratio (explained on *Question 5*), and the peak-to-valley (PV) distance, that measures the difference between the highest and lowest points on the wavefront error map, providing a direct indication of the overall magnitude of the aberration. A larger PV value suggests more severe wavefront deformation. Moreover, the optical power (OP), expressed in dioptres, relates to the focal shift introduced by the wavefront curvature.

$$OP = \frac{1}{f(m)} \tag{2}$$

Where f is the focal distance. Deviations in optical power can indicate defocus-type aberrations.

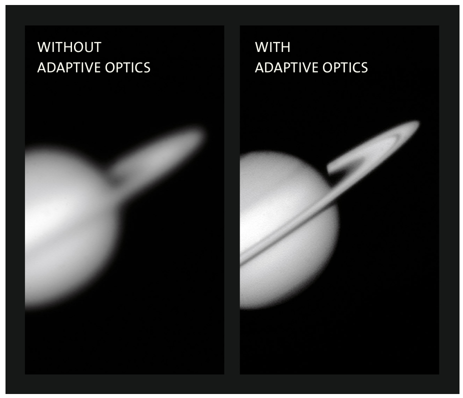

Figure 2: Comparison between uncorrected (left) and corrected (right) images using adaptive optics [5].

2 Experimental procedure

The experimental setup is designed to simulate atmospheric turbulence and evaluate the performance of an adaptive optics (AO) system:

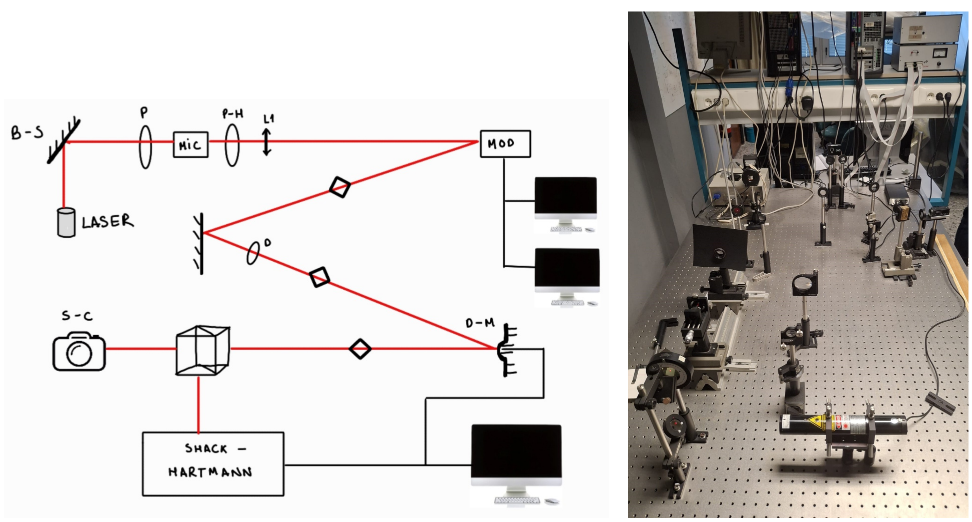

Figure 3: On the left, comparison between the schematic layout, on the right, the actual laboratory setup. A laser source, a beam splitter (B-S), a spatial filter (microscope (Mic) and a pin-hole (P-H)), a lens (L1), a phase modulator (MOD), a diaphragm (D), a deformable mirror (D-M), a scientifical camera (S-C) and a Shack-Hartmann (S-H) sensor.

The system begins with a laser emitting monochromatic light, which is collimated and polarized to ensure uniform propagation. After passing through a beam splitter, the light is directed into a spatial filtering system composed of a microscope objective and a pinhole. This spatial filter removes higher-order spatial modes and intensity noise, resulting in a clean, flat wavefront. Next, the beam passes through a collimating lens and enters the spatial light modulator (MOD), which simulates atmospheric turbulence. The MOD consists of a liquid crystal layer whose local refractive index can be altered by applied voltages, modifying the phase of the incident wavefront. The induced phase variation ϕ at each point depends on the crystal thickness d, the wavelength λ, and the refractive index n, via the expression:

$$\phi = \frac{2\pi dn}{\lambda}$$

By displaying greyscale images corresponding to selected Zernike polynomials (such as defocus or astigmatism), the MOD introduces controlled aberrations. The distorted beam is then guided through a 4-f optical system, which preserves the wavefront's spatial phase distribution. The beam is reflected by a flat mirror and reduced in diameter by a diaphragm to maintain the beam size. A second 4-f system directs the beam to the deformable mirror. It contains hexagonal actuators, each independently controlled by voltage values between -1 V and $+1$ V. These actuators modify the mirror surface to compensate for the aberrated wavefront.

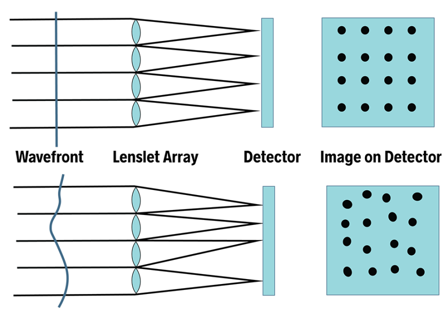

Figure 4: Shack-Hartmann wavefront sensing principle. These displacements are proportional to the local slopes of the wavefront and are used to reconstruct its shape.

After reflection, the corrected beam is split again. One part is sent to a Shack-Hartmann wavefront sensor, while the other is directed toward a scientific camera (unused in this experiment). The Shack-Hartmann sensor contains an array of microlenses that focus portions of the wavefront onto a detector. Any displacement in the focused spots indicates a slope in the wavefront, which is used to reconstruct the full phase map.

Wavefront data is analyzed using the *FrontSurfer v1.3.4* software, which allows manual deformation of the mirror. The system iteratively adjusts the mirror surface to minimize wavefront error.

3 Results and Discussion

3.1 Negative Aberration

The first test was performed by introducing a concave aberration. As shown in Figure 5 (left), the wavefront before compensation displayed a negative curvature, confirmed by the presence of concentric rings in the interferogram and a defocused PSF. Quantitatively, the aberration had a PV = 1.788 waves, an optical power OP = -0.176 D, and a low SR = 0.039, indicating poor optical quality. After manual compensation (Figure 5, right), where all actuators were set to zero voltage, the wavefront showed improvement. The updated parameters were PV = 0.869 waves, OP = -0.051 D, and SR = 0.170. These changes suggest that although the correction was not optimal, it did reduce the aberration significantly.

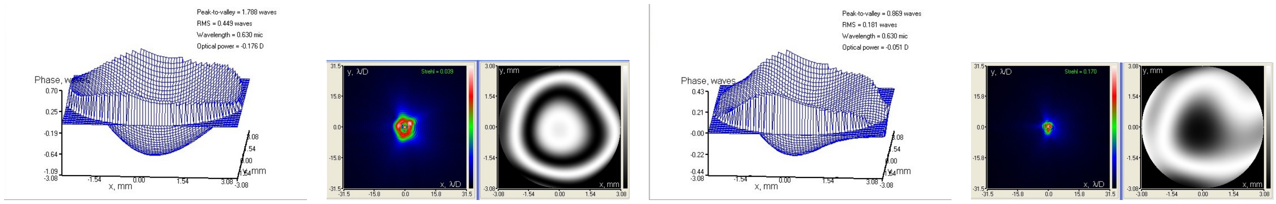

Figure 5: On the left, negative aberration before compensation. On the right, negative aberration after manual compensation.

Figure 6 presents the result after applying active feedback correction. The deformable mirror (left) adopted a convex shape, compensating for the concave aberration. The resulting wavefront (right) is flatter, and the corresponding PSF regains a more concentrated peak. The final values obtained were PV = 0.829 waves, OP = -0.048 D, and SR = 0.218, confirming that feedback correction provided the most effective compensation among the three stages.

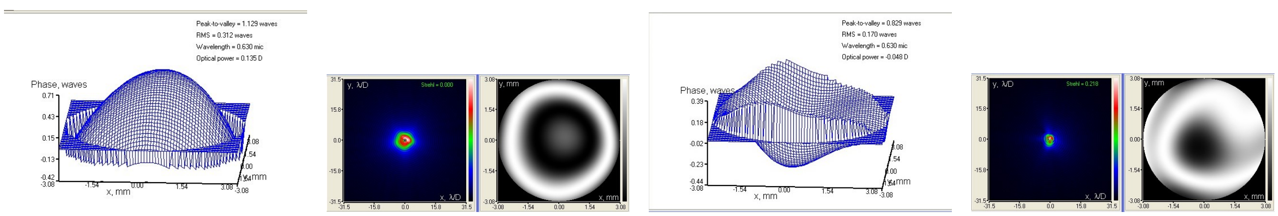

Figure 6: On the left, shape of the mirror after compensation. On the right, corrected wavefront after feedback compensation.

Figure 7 shows the final configuration of the deformable mirror. The central actuators show increased positive displacement, as expected in the compensation of a defocus.

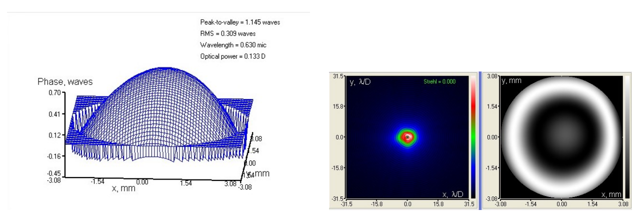

Figure 7: Shape of the mirror after feedback compensation.

3.2 Positive Aberration

The second test introduced a convex aberration, leading to a positively curved wavefront as seen in Figure 8 (left). The initial wavefront parameters were PV = 1.804 waves, OP = 0.180 D, and SR = 0.033, which indicated degradation in image quality. Manual correction was attempted by setting a constant negative voltage (-0.85 V) to the actuators. This adjustment reduced the curvature, as shown in Figure 8 (right), achieving PV = 0.533 waves, OP = -0.023 D, and SR = 0.666.

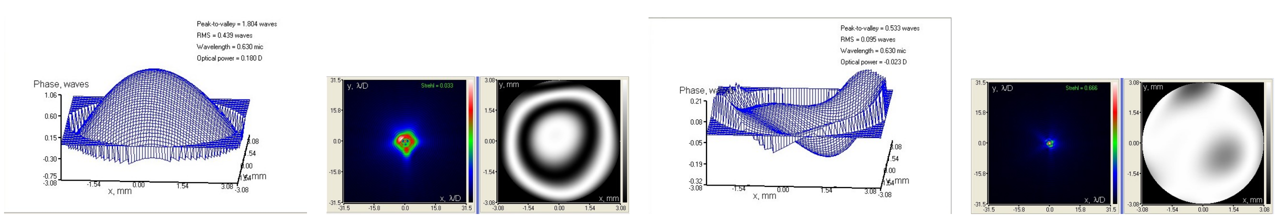

Figure 8: On the left, positive aberration before compensation. On the right, positive aberration after manual compensation.

As with the negative case, active feedback was applied, and the mirror surface shown in Figure 9 (left) adopted a concave profile to oppose the convex wavefront. However, the resulting correction did not perform as expected. Figure 9 (right) shows a distorted wavefront, and the final parameters worsened: PV = 2.549 waves, OP = 0.303 D, and SR = 0.013. This indicates that the feedback loop may have failed to converge or was affected by external disturbances during this test.

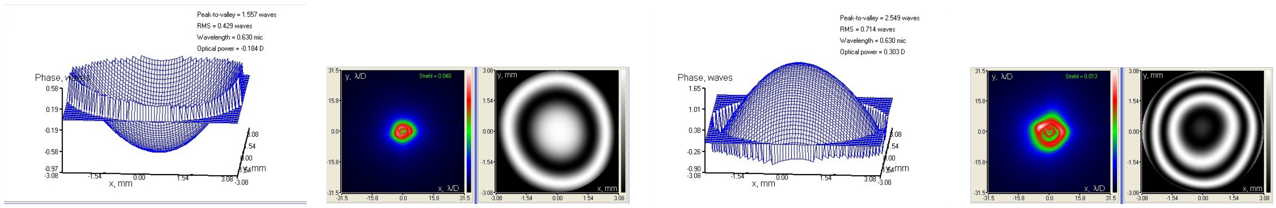

Figure 9: On the left, shape of the mirror after compensation. On the right, corrected wavefront after feedback compensation.

The final shape of the mirror, Figure 10, confirms that the compensation required stronger deformation in the peripheral actuators.

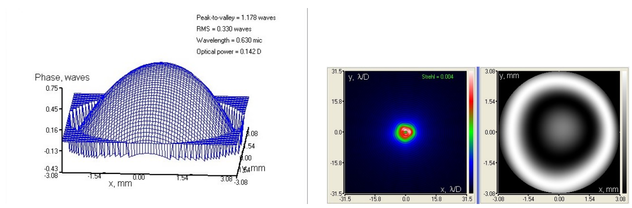

Figure 10: Shape of the mirror after feedback compensation.

4 Conclusions

The adaptive optics system demonstrated capacity to compensate for low-order aberrations introduced by the phase modulator. Both positive and negative aberrations were introduced and addressed using two approaches: manual compensation and automatic feedback-based correction through a Shack-Hartmann sensor and control software.

Manual compensation, applied via uniform voltage to all actuators, resulted in small improvements. It was particularly more effective in the case of the convex aberration, achieving a significant increase in the Strehl ratio and a reduction in wavefront distortion. In contrast, the automatic feedback correction was more consistent for the concave case, flattening the wavefront and improving optical quality. However, in the convex case, feedback compensation worsened the distortion, as evidenced by the increased PV value and reduced Strehl ratio. This performance discrepancy suggests that the correction algorithm or actuator limits may respond differently depending on the aberration's spatial profile.

For future work, a more controlled environment, better system alignment, and further tuning of the feedback algorithm could enhance repeatability and correction accuracy.

Questions

1. **Why does a star provide coherent light? Explain the Van Cittert-Zernike theorem.**

   Two points on a wave are said to be coherent when their relative phase remains constant over time. While stars are naturally incoherent sources, since each point on their surface emits light independently and across a broad range of wavelengths, the light we observe from Earth can exhibit spatial coherence due to the large distance between the star and the observer.

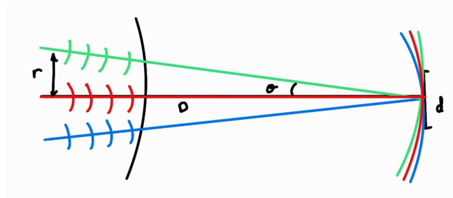

Figure 11: Light emission from a distant star. Due to the large distance D, the small wavefront segment d appears flat, and angular deviations θ from different emission points become negligible.

According to the Van Cittert-Zernike theorem, when an incoherent source is sufficiently far away, the complex degree of spatial coherence at the observation plane is given by the normalized Fourier transform of the source's intensity distribution. Mathematically, this is expressed as:

$$\Gamma(x, y) = \mathcal{F}\{I(k_x, k_y)\}$$

where $\Gamma(x, y)$ is the mutual coherence function, and $I(k_x, k_y)$ is the spatial intensity distribution of the source. This implies that the coherence properties of light improve as the observation point moves farther from the source. As stars are located at astronomical distances, the angular separation between rays emitted from different points on the star becomes extremely small ($\theta \to 0$), resulting in a nearly planar and spatially coherent wavefront.

Furthermore, the visibility of interference fringes, defined as

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

serves as a practical measure of coherence. A value of $V = 1$ corresponds to perfect coherence, whereas $V = 0$ indicates complete incoherence. This visibility function is used to determine how coherent the light from a star is, validating the theoretical prediction of the Van Cittert-Zernike theorem [3, 8].

2. **What is the Isoplanatic Patch? How to improve it?**

The Isoplanatic Patch refers to a region around a reference point in the sky over which the distortions introduced by the Earth's atmosphere are sufficiently correlated to be corrected by adaptive optics (AO) systems. Within this area, the atmospheric turbulence behaves similarly for all incoming light rays, making it possible to apply uniform phase corrections for high-resolution imaging [12].

The size of the isoplanatic patch is limited, but it can be improved using several techniques. One of the primary strategies to improve the size and effectiveness of the isoplanatic patch is through Adaptive Optics (AO) itself. AO systems use wavefront sensors and deformable mirrors to dynamically correct atmospheric distortions in real time. However, classical AO is limited by the angular range over which the wavefront distortions remain similar, typically yielding a small isoplanatic patch. Another one is the use of artificial guide stars, created by projecting a laser into the upper atmosphere to simulate a reference point for wavefront sensing when no suitable natural star is available. A more advanced method is Multi-Conjugate Adaptive Optics (MCAO), which uses multiple deformable mirrors and guide stars at different altitudes to correct turbulence across a 3D volume, improving the corrected field.

Additionally, Lucky Imaging offers an alternative to AO. It involves capturing a large number of short-exposure images and selecting only those least affected by turbulence. While it does not require a guide star, it is limited by telescope size and source brightness.

3. **How does the detected bandwidth affect the compensation process in the different steps?**

The detected bandwidth, which is the range of wavelengths processed by the optical system, has a direct impact on the accuracy of wavefront correction in adaptive optics. A broader bandwidth improves the signal-to-noise ratio, which is necessary when observing faint objects. However, it also introduces chromatic aberration, since lenses have wavelength-dependent focal lengths; each colour focuses at a slightly different point due to variations in refractive index across the spectrum.

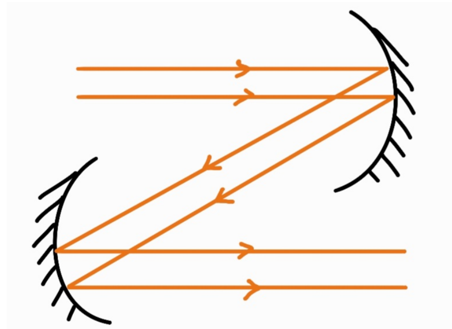

Figure 12: Corrected 4-f system using mirrors.

This effect becomes more pronounced in systems using optical glass, where microscopic shifts in the position of crystal particles alter the phase of each wavelength differently. In particular, 4-f systems using refractive elements suffer from focal plane misalignment when handling polychromatic light. To eliminate this issue, reflective optics such as mirrors are preferred, as they do not disperse wavelengths and preserve phase alignment across the spectrum [6]. Nevertheless, mirrors may degrade over time due to surface oxidation, which affects their reflectivity [9].

Moreover, components like the Shack-Hartmann sensor can also exhibit chromatic aberration, since the lenses in the array may focus different wavelengths to slightly different positions, reducing wavefront sensing accuracy.

4. **Is it possible to attain the telescope OTF using AO?**

The Optical Transfer Function (OTF) describes how spatial frequencies are transmitted through an optical system, and recovering it entirely would require perfect phase correction across all frequencies. Although adaptive optics (AO) significantly improves image quality by compensating for atmospheric turbulence, fully achieving the OTF of an ideal telescope remains practically impossible.

Several limitations prevent this: First, there is always a temporal delay between wavefront measurement and mirror correction, on the order of milliseconds, which means the system is constantly correcting outdated atmospheric conditions [12]. Second, system noise, introduced by the wavefront sensor, deformable mirror, and processing algorithms, degrades the precision of the correction [6]. Additionally, wavefront aberrations are described using Zernike polynomials, but only a finite number can be used in practice. Since an infinite series would be required to perfectly model all aberrations, the root mean square (RMS) of the residual error never truly reaches zero. This limits the ability of AO to recover high spatial frequencies and thus fully match the ideal OTF [3].

5. **What is the Strehl ratio? What is it for?**

The Strehl ratio (SR) is a dimensionless parameter used to evaluate the performance of an optical system. It quantifies the degradation of image quality due to aberrations by comparing the peak intensity of the actual point spread function (PSF) to that of an ideal, aberration-free system following an Airy distribution:

$$SR = \frac{h'}{h}$$

where h' is the maximum intensity of the aberrated PSF and h is the ideal one. A value of $SR = 1$ indicates perfect correction, while lower values reflect increasing wavefront distortion.

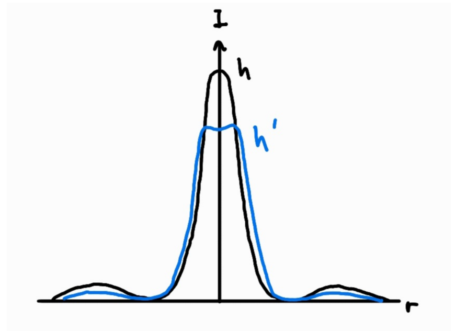

Figure 13: Comparison of PSF peak intensities. The blue curve shows an aberrated image with reduced central intensity, while the black curve represents an ideal, diffraction-limited system.

This metric provides a clear, scalar indication of how effectively a system compensates for phase aberrations introduced by the atmosphere or optical elements. Since it integrates the effects of all residual errors, the Strehl ratio is often preferred over individual wavefront parameters for assessing overall image quality. In practical terms, it helps guide the optimization of AO systems and is commonly used in astronomy and biomedical imaging to compare system performance before and after correction [10]. In combination with other parameters like peak-to-valley distance or optical power, the Strehl ratio allows for comparative evaluation of different correction states and system configurations. Its calculation is rooted in wavefront analysis and is frequently used to guide the optimization of deformable mirror adjustments and control algorithms [4].

6. **Define a 4-f system and conjugate planes in a 4-f system.**

A 4-f optical system is a fundamental configuration used in imaging and beam shaping, composed of two lenses placed at a distance equal to the sum of their focal lengths. Specifically, if lenses L_1 and L_2 have focal lengths f_1 and f_2, they are separated by $f_1 + f_2$, forming what is known as a 4-f arrangement.

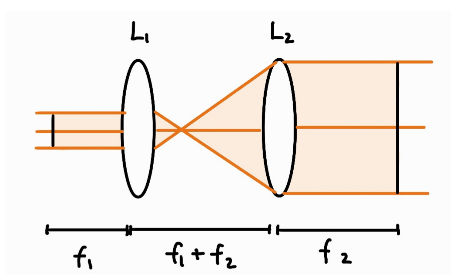

Figure 14: Standard 4-f system composed of two lenses.

This setup performs a Fourier transform of the input field at the focal plane of the first lens, and the second lens executes the inverse Fourier transform, reconstructing the original spatial field at the output plane. These input and output planes are referred to as conjugate planes, meaning that a point in one corresponds exactly to a focused point in the other. This conjugation ensures that phase and spatial information is preserved, making 4-f systems useful in adaptive optics and spatial filtering applications [2]. In practical terms, such a system maintains the relative phase of the wavefront, for preserving coherent information. It is often used to relay and process images, manipulate wavefronts, or insert filters at the intermediate Fourier plane to remove unwanted spatial frequencies [11].

7. **What is spatial frequency filtering? How does optical spatial filter work?**

Spatial frequency filtering is a technique used in optics to manipulate or enhance certain features of an image by selectively allowing or blocking specific spatial frequencies. In this context, a spatial frequency corresponds to the rate at which image intensity changes over space, high frequencies represent fine details or noise, while low frequencies correspond to broader features.

An optical spatial filter works by performing a Fourier transform of the incoming beam using a lens, projecting its spatial frequency components onto the focal plane. At this plane a filter mask is placed to block or transmit selected frequencies. Commonly, a small pinhole or opaque disk is used to eliminate high-frequency noise or unwanted diffraction patterns. After filtering, a second lens performs an inverse Fourier transform to reconstruct the modified image. This method is particularly useful in laser beam shaping, adaptive optics, and optical data processing, where it helps improve contrast, remove artifacts, or isolate specific image features. The filtering effect can be controlled by modifying the shape, size, or position of the aperture placed in the Fourier plane [1].

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